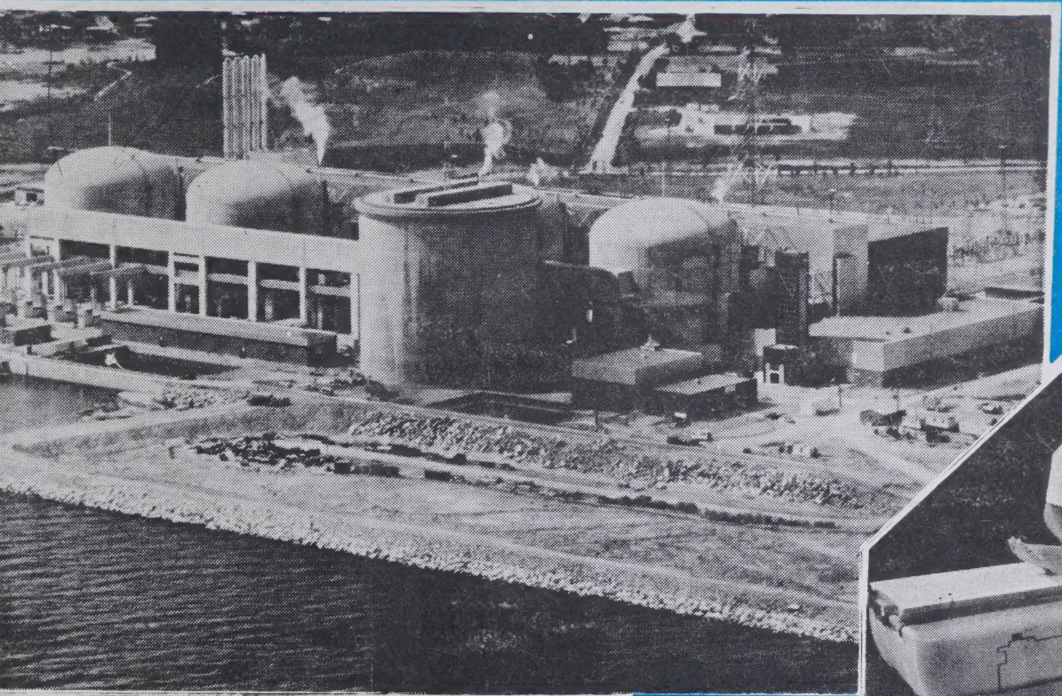
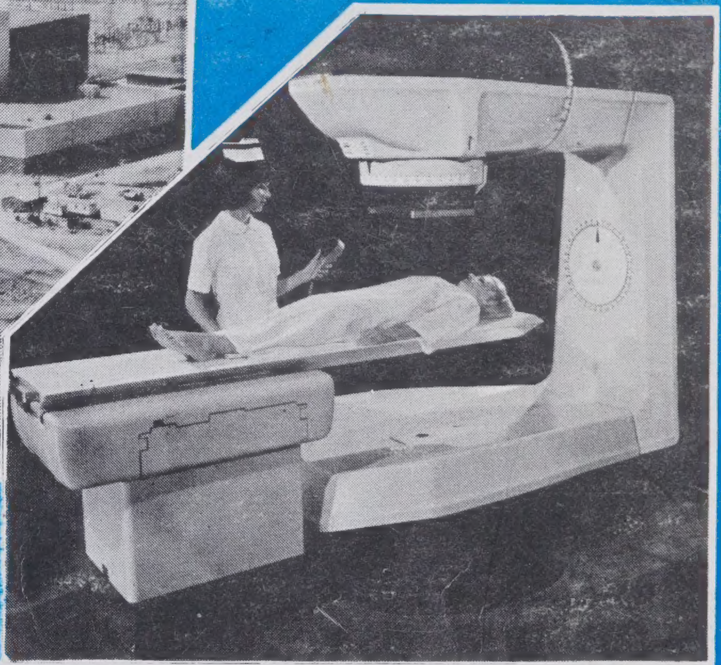
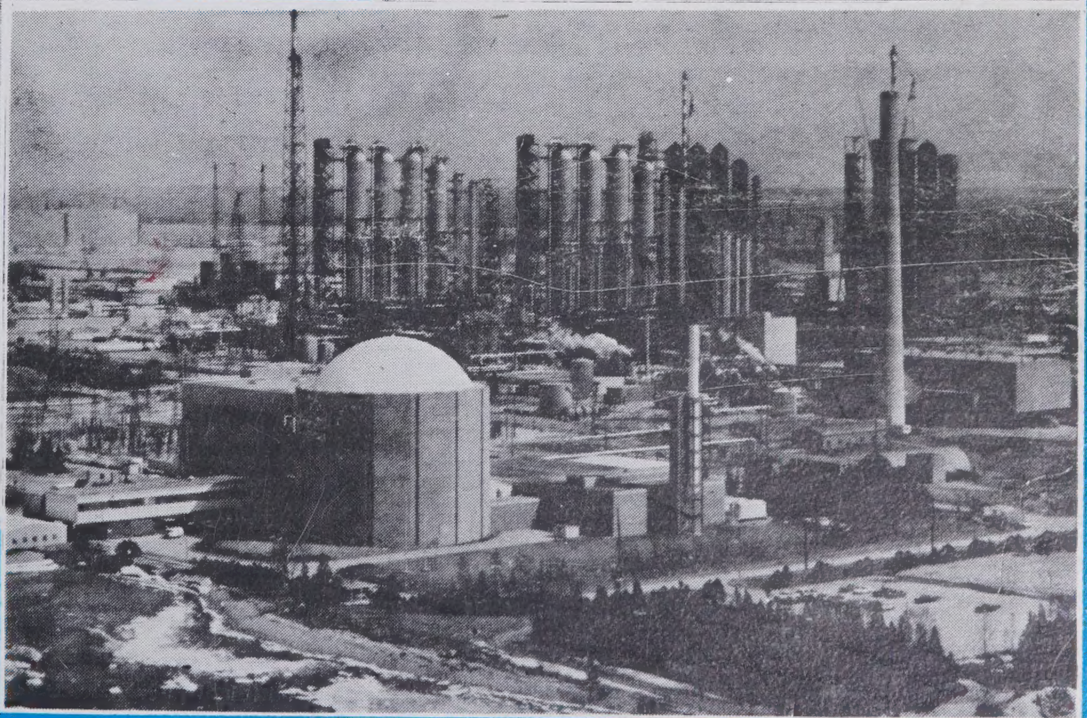
NUCLEAR CHEMISTRY







ALCHEM

Canada Canada
metric métrique

1. Radioactive Isotopes

Isotope	Half-Life*	Decay Mode**	Isotope	Half-Life*	Decay Mode**
${}^{3}_{1}H$	12.3 a	β^-	${}^{216}_{84}Po$	0.160 s	α
${}^{14}_{6}C$	5.77×10^3 a	β^-	${}^{218}_{84}Po$	3.05 min	α, β^-
${}^{24}_{11}Na$	15.0 h	β^-, γ	${}^{220}_{86}Rn$	51.5 s	α
${}^{32}_{15}P$	14.3 d	β^-	${}^{222}_{86}Rn$	3.82 d	α
${}^{30}_{16}S$	1.40 s	β^+	${}^{224}_{88}Ra$	3.64 d	α
${}^{36}_{17}Cl$	3.00×10^5 a	β^-	${}^{226}_{88}Ra$	1.62×10^3 a	α, γ
${}^{40}_{19}K$	1.30×10^9 a	β^-, γ	${}^{228}_{88}Ra$	6.70 a	β^-
${}^{45}_{20}Ca$	1.65×10^2 d	β^-	${}^{228}_{89}Ac$	6.13 h	β^-
${}^{60}_{27}Co$	5.27 a	β^-, γ	${}^{228}_{90}Th$	1.91 a	α
${}^{90}_{38}Sr$	28 a	β^-	${}^{235}_{92}U$	7.13×10^8 a	α, γ
${}^{131}_{53}I$	8.05 d	β^-, γ	${}^{239}_{94}Pu$	2.44×10^4 a	α, γ
${}^{212}_{82}Pb$	10.6 h	β^-	${}^{242}_{95}Am$	16.0 h	α, β^-
${}^{212}_{83}Bi$	60.6 min	α, β^-			
${}^{212}_{84}Po$	3.00×10^{-7} s	α			

* s = seconds, min = minutes, h = hours, d = days, a = years

** α = alpha particle, β^- = beta particle, β^+ = positron, γ = gamma photon, α, β^- = alpha & beta

2.

$\Delta H_{H_2O(s) \rightarrow H_2O(\ell)}$ =

$\Delta H_{H_2O(\ell) \rightarrow H_2O(g)}$ = 40.8 kJ/mol

$c_{H_2O(s)}$ = 2.01 J/(g·°C)

$c_{H_2O(\ell)}$ = 4.19 J/(g·°C)

$c_{H_2O(g)}$ = 2.01 J/(g·°C)

c = 3.00×10^8 m/s

$e^- = q_{e^-}$ = 1.60×10^{-19} C

N = 6.02×10^{23}/mol

Q = 9.65×10^4 C/mol$_{e^-}$

1 C = 6.24×10^{18} e^-

*1 kW·h = 3.6 MJ

*1 atm = 101.325 kPa

*1 A = 1 C/s

*1 V = 1 J/C = 96.5 kJ/mol$_{e^-}$

*1W = 1 J/s

*1 t = 1000 kg = 1 Mg

* exact values

ALCHEM

M

istry

data sheet

3. Atomic Molar Masses of Isotopes

${}^{0}_{-1}e$ = 0.000 548 6	${}^{4}_{2}\alpha$ = 4.001 50	${}^{16}_{8}O$ = 15.994 91
${}^{1}_{1}p$ = 1.007 276 5	${}^{4}_{2}He$ = 4.002 60	${}^{35}_{17}Cl$ = 34.968 85
${}^{1}_{0}n$ = 1.008 665 0	${}^{5}_{2}He$ = 5.012 3	${}^{56}_{26}Fe$ = 55.934 9
${}^{1}_{1}H$ = 1.007 825	${}^{5}_{3}Li$ = 5.012 5	${}^{206}_{82}Pb$ = 205.974 5
${}^{2}_{1}H$ = 2.014 0	${}^{12}_{6}C$ = 12 (exactly)	${}^{210}_{84}Po$ = 209.982 9
${}^{3}_{1}H$ = 3.016 05	${}^{14}_{7}N$ = 14.003 07	${}^{235}_{92}U$ = 235.043 9
${}^{3}_{2}He$ = 3.016 03	${}^{15}_{7}N$ = 15.000 11	${}^{238}_{92}U$ = 238.050 8

4. Relative Strengths of Oxidizing and Reducing Agents

SOA (Decreasing Strength of Oxidizing Agents) — SRA (Decreasing Strength of Reducing Agents)

Half-reaction	**$E°$ (V)
$^{***}F_{2(aq)} + 2e^- \rightleftharpoons 2F^-_{(aq)}$	+2.87
$MnO^-_{4(aq)} + 8H^+_{(aq)} + 5e^- \rightleftharpoons 4H_2O_{(\ell)} + Mn^{2+}_{(aq)}$	+1.49
$Au^{3+}_{(aq)} + 3e^- \rightleftharpoons Au_{(s)}$	+1.42
$^{***}Cl_{2(aq)} + 2e^- \rightleftharpoons 2Cl^-_{(aq)}$	+1.36
$Cr_2O^{2-}_{7(aq)} + 14H^+_{(aq)} + 6e^- \rightleftharpoons 7H_2O_{(\ell)} + 2Cr^{3+}_{(aq)}$	+1.33
$N_2H^+_{5(aq)} + 3H^+_{(aq)} + 2e^- \rightleftharpoons 2NH^+_{4(aq)}$	+1.27
$O_{2(g)} + 4H^+_{(aq)} + 4e^- \rightleftharpoons 2H_2O_{(\ell)}$	+1.23
$2IO^-_{3(aq)} + 12H^+_{(aq)} + 10e^- \rightleftharpoons 6H_2O_{(\ell)} + I_{2(aq)}$	+1.19
$Br_{2(aq)} + 2e^- \rightleftharpoons 2Br^-_{(aq)}$	+1.09
$Hg^{2+}_{(aq)} + 2e^- \rightleftharpoons Hg_{(\ell)}$	+0.85
$2NO^-_{3(aq)} + 4H^+_{(aq)} + 2e^- \rightleftharpoons 2H_2O_{(\ell)} + N_2O^*_{4(g)}$	+0.81
$Ag^+_{(aq)} + e^- \rightleftharpoons Ag_{(s)}$	+0.80
$Fe^{3+}_{(aq)} + e^- \rightleftharpoons Fe^{2+}_{(aq)}$	+0.77
$O_{2(g)} + 2H^+_{(aq)} + 2e^- \rightleftharpoons H_2O_{2(\ell)}$	+0.68
$I_{2(aq)} + 2e^- \rightleftharpoons 2I^-_{(aq)}$	+0.54
$O_{2(g)} + 2H_2O_{(\ell)} + 4e^- \rightleftharpoons 4OH^-_{(aq)}$	+0.40
$Cu^{2+}_{(aq)} + 2e^- \rightleftharpoons Cu_{(s)}$	+0.34
$Sn^{4+}_{(aq)} + 2e^- \rightleftharpoons Sn^{2+}_{(aq)}$	+0.15
$2H^+_{(aq)} + 2e^- \rightleftharpoons H_{2(g)}$	0.00
$Pb^{2+}_{(aq)} + 2e^- \rightleftharpoons Pb_{(s)}$	-0.13
$Sn^{2+}_{(aq)} + 2e^- \rightleftharpoons Sn_{(s)}$	-0.14
$Ni^{2+}_{(aq)} + 2e^- \rightleftharpoons Ni_{(s)}$	-0.23
$Co^{2+}_{(aq)} + 2e^- \rightleftharpoons Co_{(s)}$	-0.28
$Cd^{2+}_{(aq)} + 2e^- \rightleftharpoons Cd_{(s)}$	-0.40
$Fe^{2+}_{(aq)} + 2e^- \rightleftharpoons Fe_{(s)}$	-0.41
$Cr^{3+}_{(aq)} + 3e^- \rightleftharpoons Cr_{(s)}$	-0.74
$Zn^{2+}_{(aq)} + 2e^- \rightleftharpoons Zn_{(s)}$	-0.76
$2H_2O_{(\ell)} + 2e^- \rightleftharpoons 2OH^-_{(aq)} + H_{2(g)}$	-0.83
$2NO^-_{3(aq)} + 2H_2O_{(\ell)} + 2e^- \rightleftharpoons 4OH^-_{(aq)} + N_2O^*_{4(g)}$	-0.85
$SO^{2-}_{4(aq)} + H_2O_{(\ell)} + 2e^- \rightleftharpoons SO^{2-}_{3(aq)} + 2OH^-_{(aq)}$	-0.92
$Al^{3+}_{(aq)} + 3e^- \rightleftharpoons Al_{(s)}$	-1.66
$Mg^{2+}_{(aq)} + 2e^- \rightleftharpoons Mg_{(s)}$	-2.37
$Na^+_{(aq)} + e^- \rightleftharpoons Na_{(s)}$	-2.71
$Ca^{2+}_{(aq)} + 2e^- \rightleftharpoons Ca_{(s)}$	-2.76
$K^+_{(aq)} + e^- \rightleftharpoons K_{(s)}$	-2.92
$Li^+_{(aq)} + e^- \rightleftharpoons Li_{(s)}$	-3.04

* Colorless $N_2O_{4(g)}$ decomposes into brown $NO_{2(g)}$.

** Reduction potentials for 1.0 mol/L aqueous solutions at 25°C and 101 kPa.

*** Shown as aqueous for convenience; actually measured in gaseous form.

5. Molar Heats of Formation*

t = 25°C P = 101 kPa

Name	Formula	H_f (kJ/mol)
acetic acid	$CH_3COOH_{(\ell)}$	-488.6
acetone	$CH_3COCH_{3(\ell)}$	-115.6
acetylene	$C_2H_{2(g)}$	+226.9
aluminum oxide	$Al_2O_{3(s)}$	-1676.8
ammonia	$NH_{3(g)}$	- 46.1
benzene	$C_6H_{6(\ell)}$	+ 82.8
butane	$C_4H_{10(\ell)}$	-124.8
calcium carbide	$CaC_{2(s)}$	- 62.8
calcium carbonate	$CaCO_{3(s)}$	-1205.8
calcium chloride	$CaCl_{2(s)}$	-795.5
calcium oxide	$CaO_{(s)}$	-636.0
carbon dioxide	$CO_{2(g)}$	-393.6
carbon disulfide	$CS_{2(\ell)}$	+117.2
carbon monoxide	$CO_{(g)}$	-110.5
copper(II) oxide	$CuO_{(s)}$	-166.6
copper(I) oxide	$Cu_2O_{(s)}$	-155.3
ethane	$C_2H_{6(g)}$	- 84.6
ethanol	$C_2H_5OH_{(\ell)}$	-277.6
ethene (ethylene)	$C_2H_{4(g)}$	+ 52.3
ethylene dichloride	$C_2H_4Cl_{2(\ell)}$	-166.3
ethylene glycol	$C_2H_4(OH)_{2(\ell)}$	-455.0
ethylene oxide	$C_2H_4O_{(g)}$	- 51.1
glucose	$C_6H_{12}O_{6(s)}$	-900.0
hydrogen chloride	$HCl_{(g)}$	- 92.6
hydrogen iodide ($I_{2(s)}$)	$HI_{(g)}$	+ 26.0
hydrogen iodide ($I_{2(g)}$)	$HI_{(g)}$	- 5.0
hydrogen peroxide	$H_2O_{2(\ell)}$	-188.0
hydrogen sulfide	$H_2S_{(g)}$	- 20.5
iron(III) oxide	$Fe_2O_{3(s)}$	-822.7
methane	$CH_{4(g)}$	- 74.9
methanol	$CH_3OH_{(\ell)}$	-238.6
nitrogen dioxide	$NO_{2(g)}$	+ 33.9
nitrogen monoxide	$NO_{(g)}$	+ 90.4
nitromethane	$CH_3NO_{2(\ell)}$	- 89.2
octane	$C_8H_{18(\ell)}$	-208.7
propane	$C_3H_{8(g)}$	-103.8
sucrose	$C_{12}H_{22}O_{11(s)}$	-1742.0
sulfuric acid	$H_2SO_{4(\ell)}$	-812.2
sulfur dioxide	$SO_{2(g)}$	-297.3
2,2,4-trimethylpentane	$C_8H_{18(\ell)}$	-224.6
sulfur trioxide	$SO_{3(g)}$	-396.1
vinyl chloride	$C_2H_3Cl_{(g)}$	+ 33.9
water (liquid)	$H_2O_{(\ell)}$	-286.0
water (vapor)	$H_2O_{(g)}$	-242.0

* *Molar heats of formation for elements in natural occurring form are assumed to be zero.*

Refer to the *CRC Handbook of Chemistry and Physics* for further data.

AUTHORS OF ALCHEM ELECTIVES

Frank Jenkins ALCHEM Director
Queen Elizabeth Composite High School
Edmonton, Alberta
George Klimiuk Harry Ainlay Composite High School
Dick Tompkins Queen Elizabeth Composite High School
Oliver Lantz Harry Ainlay Composite High School
Dale Jackson Victoria Composite High School
Tom Mowat Ross Sheppard Composite High School
Hans van Kessel Queen Elizabeth Composite High School

CONSULTANTS

Dr. Ron Cavell Department of Chemistry, University of Alberta
Dr. Heidi Kass Department of Science Education, University of Alberta
Dr. Marshall Nay Department of Science Education, University of Alberta
Dr. Joseph Takats Department of Chemistry, University of Alberta

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PREFACE

Introduction

ALCHEM is the result of many educators joining together to write and teach a chemistry program that would meet the needs of todays students. Through six years of classroom experimentation with over 50 000 students, the program has come to its present form. In answer to the request made by teachers and students throughout the country, ALCHEM has become the most descriptive and applied chemistry material available on the market today.

This approach of applied and descriptive chemistry is integrated into the textual material, labs, demonstrations and classroom exercises to an extent never done before.

Environmental, consumer and industrial chemistry are found throughout the program as well as many historical references and biographies on famous chemists. All this has been achieved without sacrificing a high level of chemistry. The chemistry content is not watered down. You will see from the unique design of the format, that the material has an easy-to-learn-from classroom approach. Students like using the program and their achievement level is high. Test results prove that ALCHEM students have significantly outperformed students on other programs and they have shown an equal or higher interest in chemistry.

Organization of the Program

In its present form there are three core books, ALCHEM 10, ALCHEM 20 and ALCHEM 30, which can be used for two half-courses and one full course, respectively, or with two full courses. Each core book is divided into units that cover specific topics. Within each unit, labs, demos and exercises are integrated in a logical sequence with the textual material. The ALCHEM 20 and 30 each have a complete review unit that acts as a refresher for the student who may not be familiar with previous content. It is our experience that a student can begin the program quite easily even if he or she starts with ALCHEM 30. Each core book can stand on its own.

In addition to the three core books, seven elective units are available to give added dimension to special topics selected by students or teachers. The core units emphasize the concepts of chemistry and bring in the applied and descriptive chemistry where possible. The elective units emphasize the applied and descriptive chemistry and bring in the concepts of chemistry where possible. There is a balance of organic and inorganic electives. The elective units are; *Foods and Their Analogs, Athabasca Tar Sands, Analytical Chemistry, Nuclear Chemistry, Metallurgy and Corrosion, Ethylene and its Derivatives,* and *Alberta Chemical Industries.*

The strongest feature in the whole program is that all the material has been reworked and revised many times to make it pedagogically sound for both the student and the teachers. Many new ways of approaching traditionally difficult chemistry concepts have resulted in the student finding the new approaches easy to understand. For example, the *Gravimetric Stoichiometry* unit is prepared for so thoroughly in the earlier units that it becomes a summary unit. Seven types of bonding in the *Chemical Bonding* unit are explained simply in terms of simultaneous attractions. All questions in the *Energy* unit are done by the approach of heat lost equals heat gained. All redox and acid-base reactions are done by a single five step method.

Another strong feature is the format. In many respects the teacher preparation time has been redirected. The students have the complete program in front of them in their loose leaf binders. Prepared exercises for the student to complete are placed next to the topic covered. Here the organization of the material minimizes the students confusion found in the use of other textbooks. The format of the exercises makes it easier for the teachers to concentrate on classroom strategies. Because quality classroom activities are already developed in the core material and the electives, the teacher has more time to devote to class and individual questions, implementing a wider variety of teaching strategies, spending more professional time on test making and reading, and preparing elective materials.

In addition to the above mentioned texts, an ALCHEM periodic table is available within each core book. Periodic table wall charts are also available. ALCHEM 30 includes the ALCHEM data sheet. Test item banks are available for ALCHEM 10, 20 and 30.

Special Features

The ALCHEM material was developed by the authors in consultation with science curriculum advisors in both education and chemistry at the University of Alberta. Through the years of piloting, many of the authors and pilot teachers devoted much of their free time and expertise to the improvement and enjoyment of their profession by producing a better chemistry program. ALCHEM serves as a model to what can be accomplished through local curriculum development projects. It also shows what dedicated classroom teachers can do, for without them, we would not have this classroom oriented approach. The over 120 pilot teachers that worked with the program, contributed feedback that is not normally found in other textbook projects. Their comments and criticisms helped make the material work better in the classroom.

For those concerned about the rising cost of textbooks, the ALCHEM prices are very reasonable. In fact, the ALCHEM program costs less than the conventional textbook program even if you amortize the costs of the conventional text over a three to five year period.

The illustrations are of a comic nature to add some fun and enjoyment to the serious chemistry topics. They are designed to bring humor into the classroom—to let the student feel that chemistry does not have to be a heavy subject.

The United States National Institution of Education Curriculum Development Task Force has found that a major reason for the failure of million dollar curriculum projects in the past, has been the lack of significant participation by classroom teachers. ALCHEM is successful because classroom teachers created the program and students find it to be an enjoyable and rewarding learning experience.

The Symons Report has stated that, "A curriculum in this country that does not help Canadians in some way to understand the physical and social environment in which they live and work...cannot be justified in either academic or practical terms. It is essential, from the standpoint of both sound balanced scholarship and of practicality, that studies of the Canadian situation occupy an appropriate place in the curriculum...". ALCHEM is an example of a program that fulfills many of the recommendations made in the Symons Report. ALCHEM is truly a Canadian science program.

The major recommendation of the International Conference on New Directions in Chemistry Curriculum held in 1978 at McMaster University stated that a greater proportion of applied and descriptive chemistry be integrated into chemistry core and elective curriculums and textbooks. In order to accomplish this addition some of the most theoretical topics have to be cut. ALCHEM serves as a unique example of how the applied and descriptive chemistry can be integrated into curriculum materials.

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ALCHEM MATERIALS

ALCHEM 10

Unit A: Elements and the Periodic Table
Unit B: Compounds, Bonding and Nomenclature
Unit C: Chemical Reactions
Unit D: The Mole
Unit E: Gravimetric Stoichiometry

ALCHEM 20

Unit F: Review of ALCHEM 10
Unit G: Chemical Bonding
Unit H: Organic Chemistry
Unit I: Solutions

ALCHEM 30

Unit K: Review of ALCHEM 10 & 20
Unit L: Energy
Unit M: Electrochemistry
Unit N: Acids and Bases

ALCHEM Electives (Available separately) (level)

Unit J: Analytical Chemistry (20, 30)
Unit O: Foods and Their Analogs (30, 20)
Unit - The Athabasca Tar Sands (30, 20)
Unit P: Ethylene and its Derivatives (30)
Unit S: Alberta Chemical Industries (10)
Unit T: Metallurgy and Corrosion (30)
Unit U: Nuclear Chemistry (30, 20)

Other ALCHEM Materials

1. ALCHEM 10 Teachers' Guide
2. ALCHEM 20 Teachers' Guide
3. ALCHEM 30 Teachers' Guide
4. ALCHEM Electives Teachers' Guide
5. ALCHEM periodic table (student)
6. ALCHEM 30 data sheet (student)
7. ALCHEM 10 Test Item Bank (1979)
8. ALCHEM 20 Test Item Bank (1979)
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10. ALCHEM periodic table (wall chart) - Side 1 (1979)
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13. ALCHEM 30 data sheet (wall chart) - Side 2 (1979)
14. **Tar Sands wall chart**
15. **ALCHEM mole poster**
16. **ALCHEM illustrated, biography posters**

PREREQUISITE KNOWLEDGE

Unit Prerequisite Knowledge

Before starting Unit U, *Nuclear Chemistry*, the student should be able to:

1. use simple SI units, symbols and prefixes
2. use the rules for simple mathematical operations involving significant digits and units
3. list the relative mass and charge of a proton, neutron and an electron
4. list the number of protons and electrons in any atom or simple ion
5. explain the basic structure of an atom using the Bohr model
6. recognize that the mole is a quantity of matter containing Avogadro's number of particles
7. define molar mass as the mass of one mole of atoms, molecules, formula units, etc.
8. distinguish between exothermic and endothermic changes
9. relate bond energy, potential energy and net energy change of a reaction
10. understand and use the ΔH notation for the heat of reaction

Quantity	Quantity Symbol	SI Unit Symbol
mass	***m***	g
number of moles	***n***	mol
molar mass	***M***	g/mol
volume	***v***	L
molar concentration	***C***	mol/L
energy	***E***	J

Unit Objectives

Upon completion of Unit U, *Nuclear Chemistry*, the student should be able to:

U1. relate some of the history background leading to the discovery of radioactivity
U2. describe the nuclear particles and radiations
U3. define radioactivity, isotope, radioisotope and mass number
U4. describe in general terms how radiation is detected
U5. discuss the evidence for the nuclear structure of atoms
U6. use the isotope notation to determine the structure of isotopes
U7. account for the stability of nuclei in terms of nuclear binding energy, neutron to proton ratio and odd-even nature of the number of neutrons and protons
U8. complete and balance nuclear equations
U9. identify four main types of nuclear reactions.
U10. explain the rate of decay of radioactive isotopes in terms of half-life
U11. write equations for neutron and proton decay to explain the origin of beta particles
U12. calculate the amount of isotope remaining and the initial amount using the radioactive decay law
U13. define transmutation, nuclear fission and nuclear fusion
U14. distinguish between critical and supercritical mass
U15. discuss nuclear fission and fusion as sources of controlled nuclear energy
U16. relate the evolution of the elements to the evolutionary sequence of nuclear processes occurring in stars
U17. describe in terms of changes in nuclear binding energy the source of energy in nuclear reactions
U18. calculate the energy associated with nuclear reactions
U19. calculate nuclear binding energy of a nucleus
U20. compare nuclear and conventional power plants
U21. discuss the viability of using nuclear reactors as a source of energy
U22. describe the nuclear fission process in nuclear power plants
U23. discuss the history of nuclear power in Canada
U24. compare heavy water with light (ordinary) water
U25. explain in general terms the process involved in the manufacture of heavy water
U26. describe the fuel, neutron moderator and coolant and their use in the CANDU reactor
U27. list and explain three types of safety and/or control features of the CANDU reactor
U28. list some of the advantages and disadvantages of the CANDU system
U29. discuss the main difference(s) between CANDU reactors and other nuclear reactors
U30. list six main applications of nuclear reactors
U31. recognize examples of the application of radioisotopes to industry, agriculture and medicine
U32. explain in general terms the operation and purpose of breeder reactors

COVER PHOTOGRAPHS

A) Pickering "A" Nuclear Generating Station of Ontario Hydro.
B) The Bruce Heavy Water Plant with the Douglas Point Nuclear Power Station in the foreground.
C) Detailed studies of environment and life processes are made around nuclear sites.
D) A Theratron 780 cancer therapy machine manufactured by AECL Commercial Products.

NUCLEAR CHEMISTRY
DISCOVERY OF RADIOACTIVITY

Introduction

Nuclear energy, as a source of electrical power, is well established in industrialized countries and becoming significant in developing countries. However many public discussions of nuclear power are often conducted in a haze of misinformation and evoke strong emotional reactions. An understanding of the principles, applications and limitations of nuclear energy is necessary for rational discussions and decisions.

Unit U, *Nuclear Chemistry*, is consistent with the ALCHEM philosophy of descriptive and applied chemistry to promote an understanding of socially important physical environments. The subject is introduced historically with the discovery of radioactivity and the development of a nuclear model. The transmutation (conversion) of elements, as evidenced by radioactivity, is generalized into four main types of nuclear reactions. Energy changes in nuclear reactions completes the basic theory and leads into the utilization of the vast amounts of energy by nuclear reactors to supply electrical power. Further applications of nuclear reactors provide many useful chemicals and technologies for industry, agriculture and medicine. The emphasis throughout most of this unit is purposely placed on the Canadian CANDU reactor system which has received international recognition for design, safety and efficiency.

Discovery of Radioactivity

One of the important events leading to the discovery of radioactivity was made in 1896 by the French scientist Henri Becquerel (1852-1908). Becquerel's work was motivated by the invention of the Crookes tube and by Roentgen's discovery of X-rays. In trying to find other sources of X-rays, Becquerel studied certain substances, notably uranium minerals, that fluoresce when exposed to sunlight. On one occasion he found that a photographic plate, which had been *accidentally* placed in a drawer in contact with some uranium minerals, had become streaked. (Another of the many examples of serendipity, the accidental discovery of something valuable, in science.) Since the photographic plate had been wrapped in paper to protect it from the action of sunlight, Becquerel concluded that some undiscovered element or elements were emitting penetrating radiation which would pass through thick layers of paper. Becquerel had discovered that *radiation* is given off spontaneously from certain naturally occurring substances. This phenomenon, reported in February, 1896, was called *radioactivity.*

Following Becquerel's discovery, Marie Curie (1867-1934) and her husband, Pierre Curie (1859-1906) became involved in the analysis of uranium ore to determine what element or elements present in the ore produced radioactivity. The Curies soon learned that uranium and uranium compounds are mildly radioactive, but that one uranium ore (pitchblende) had four times the radioactivity which could be accounted for by its uranium content. By July, 1898 the Curies announced the existence of a new radioactive element. They named the new element polonium in honor of Madame Curie's native Poland. Though polonium was four hundred times more radioactive than uranium, the minute quantity of polonium could not account for the great radioactivity of pitchblende. Subsequently the Curies spent four years isolating one-tenth of a gram of the bromide of another element from several tonnes of pitchblende. This new element proved to be at least one million times as radioactive as the same mass of uranium. Because of its extreme radioactivity the Curies named the new element *radium.*

Since the Curies began their work, over forty naturally occurring radioactive elements have been found. Many of these elements have several isotopes - atoms of elements that differ in the number of neutrons in the nucleus. Naturally occurring isotopes that spontaneously emit radiation are called *natural radioactive isotopes or natural radioisotopes.*

Types of Radioactivity

The discovery of radioactivity by Becquerel aroused the interest of many scientists. One scientist whose work significantly contributed to the understanding of radioactivity was Ernest Rutherford (1871-1937). Rutherford and his associates showed that natural radioactivity resulted from a series of disintegrations in which elements became transmuted (changed) into other elements. Rutherford in his experiments identified three types of rays that may be emitted in the radioactive process. He named the radiation types *alpha* (α), *beta* (β) and *gamma* (γ) rays.

Table U1
Characteristics of Nuclear Radiations

Radiation	Molar Mass (g/mol)	Approximate Speed at Emission	Penetration in Air	Effective Barrier
Alpha	4.001 50	variable - less than 10 % the speed of light*	a few centimetres	a sheet of paper
Beta	0.005 486	variable - up to 90 % the speed of light	a few metres	1 to 2 mm of metal
Gamma	zero	speed of light	unlimited	1 m of lead or concrete

*The speed of light (c) is 3.00×10^8 m/s or 0.300 Gm/s.

NUCLEAR CHEMISTRY
PARTICLES AND RADIATION OF NUCLEAR ORIGIN

Nuclear Radiation and Nuclear Particles

It is an oversimplification to describe the nucleus only in terms of protons and neutrons. Presently about 30 different particles have been identified as being of nuclear origin. For purposes of this unit consideration of only the particles and radiations outlined in the following table is important.

Table U2
Properties of Nuclear Radiations and Nuclear Particles

Particle or Radiation	Symbols[1] Used in Unit	Alternate Symbols	Electrical Charge	Atomic[2] Number	Mass[3] Number
alpha particle (helium nucleus)	${}^{4}_{2}\alpha$	α, ${}^{4}_{2}He$	2+	2	4
beta-negative particle (high energy electron)	${}^{0}_{1-}\beta$	β^-, ${}^{0}_{1-}e$, e^-	1-	1-	0
beta-positive particle (positron)	${}^{0}_{1}\beta$	β^+, ${}^{0}_{1}e$, e^+	1+	1	0
gamma ray (high energy photon)	γ		0	0	0
neutron	${}^{1}_{0}n$	n	0	0	1
proton	${}^{1}_{1}p$	p	1+	1	1

Notes:

1. There are many symbols in common usage. The first symbol given is the one most commonly used in this unit, particularly for nuclear reactions. The superscript and subscript refer to mass number and atomic number respectively.
2. The atomic numbers of nuclear particles and radiations are best interpreted as the charges.
3. The mass number of nuclear particles and radiations is the sum of the number of protons and neutrons.

Exercise

Define the following terms.

1. fluoresce

2. radioactivity

3. isotope

4. radioisotope

5. transmutation

NUCLEAR CHEMISTRY
DETECTING RADIOACTIVITY — DEMO U1

Detecting Radioactivity - Demo U1

Purpose:

To investigate some methods by which radioactivity can be detected.

Materials:

Part A
- radioactive source
- cloud chamber
- light source
- alcohol (2-propanol)
- dry ice

Part B
- Geiger counter
- lead shield

Predemo Information:

1. Cosmic Rays

Cosmic rays are naturally occurring radiation that crash into the Earth's atmosphere from outer space. At sea level, cosmic rays consist of at least seven different types of particles and radiation. The intensity and composition of this cosmic shower fluctuates, but is always present.

2. Cloud Chambers

In a closed container at a given temperature a liquid will reach an equilibrium with its vapor. The atmosphere above the liquid surface is said to be saturated. (The atmosphere contains the maximum amount of vapor at that temperature.) Supersaturation, a relatively unstable condition, occurs when the amount of vapor present is higher than the equilibrium value. Charged particles in a supersaturated atmosphere serve as starting points for the growth of visible droplets. *Vapor trails* (like those of a high flying jet on a clear day) may be observed and measured in a cloud chamber when supersaturated vapor condenses on charged particles (ionized gas) produced by radiation.

3. Geiger Counters

A geiger tube basically consists of two oppositely charged metal plates several centimetres apart surrounded by an inert gas. Radiation entering the tube collides with gas molecules producing charged particles (ions and electrons). These charged particles can upon further collisions produce more charged particles. In a very short time an avalanche of more and more ions and electrons are produced. The charged particles are attracted to the charged plates. This burst of current is signalled in a Geiger counter by an audible click.

Procedure:

Part A: The Cloud Chamber

The cloud chamber apparatus should be set up according to accompanying instructions. The usual procedure involves the following steps. 1. Place several millilitres of alcohol into the cloud chamber. Rotate the cloud chamber on its side to moisten the absorbant material on the sides. 2. Position the radioactive source inside the chamber. 3. Set the chamber on a piece of dry ice about the size of the bottom of the chamber. 4. Position a light source so the light is directed from the side of the cloud chamber. 5. To obtain a supersaturated vapor, clear the atmosphere of charged species by using a battery or by rubbing the top of the chamber with a silk cloth. 6. Vapor trails, with or without the radioactive source in place, should be observed in about 5 min.

Part B: The Geiger Counter

1. Bring the radioactive source near the Geiger counter and note the count rate.
2. Shield the source (or take the source far enough away that radiation from it does not reach the counter) and see if the counting stops entirely. The counting rate produced by factors other than the source is referred to as *background*.

NUCLEAR CHEMISTRY
DETECTING RADIOACTIVITY — DEMO U1

Questions:

1. What is meant by the term *background radiation?*

2. Explain the source of and evidence for this background radiation.

3. Charged particles caused by radiation in a cloud chamber act as *condensation nuclei.* Explain this term and give a common everyday example.

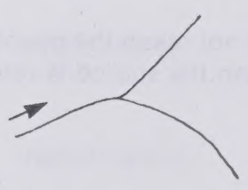
4. Of the radiations listed in Table U2, which ones would be directly visible in a cloud chamber? Explain briefly.

5. Of the radiations listed in Table U2, which ones would be detectable by a Geiger counter? Explain briefly.

(Optional)

6. Alpha particles produce short, thick vapor trails in a cloud chamber, whereas, beta particles produce long, thin trails. Propose a possible explanation for this difference.

7. Using the background information presented, propose a possible explanation for the vapor trail given below.



NUCLEAR CHEMISTRY
THE NUCLEAR ATOM

The Rutherford (Nuclear) Model

In 1911, Ernest Rutherford presented convincing evidence for the nuclear structure of atoms. In his investigations of the nature of radiation emitted from the element uranium, Rutherford performed the classic experiment which established the existence of the nucleus in atoms. In this experiment, Rutherford and his students, Hans Geiger and Ernest Marsden, placed a radioactive source of alpha rays (positively charged helium ions) behind a lead shield. A narrow beam of alpha rays was allowed to pass through a hole in a lead shield. This beam was directed against a very thin film of metal foil made from malleable metals such as gold, silver or copper. These metal films were fabricated to a thickness of about 10 000 atoms or about 1×10^{-9} m (1nm). Behind the metallic foil they placed a screen coated with zinc sulfide which would scintillate when struck with alpha particles. Rutherford observed that about 99.9% of the alpha particles passed through the foil undeflected from their paths; however, some alpha particles were deflected from their straight paths and a few were reflected back towards the source.

Based on mathematical analysis of the number of particles that were deflected per unit time as a function of the angle of deflection. Rutherford proposed the following explanations for the alpha ray scattering experiment.

1. Atoms contain a small, highly massive nucleus in the center of the atom. This nucleus contains most of the mass of the atoms and all of the positive charge. The diameter of the nucleus was calculated to be about 10^{-15} m or 10 000 times smaller than the diameter of the atom. When an alpha particle directly approaches a nucleus, it is repelled back along the incoming path. An alpha particle passing close to the nucleus is repelled and deflected from its original path.

2. Electrons, located outside the nucleus, by their motion occupy most of the total volume of the atom. Most of the alpha particles pass through unhindered because the atom is mostly empty space.

Since Rutherford first proposed the nuclear model of the atom, no experimental results have been obained that contradict this model. An important theoretical question that follows is; if the nucleus is composed of positively charged protons and uncharged neutrons, how can the particles stay so close together in the nucleus? It is now believed that when protons and neutrons approach within one or two diameters of each other (about 10^{-15} m) there is a very strong force of attraction between them. This *nuclear force* is about 100 times larger than the electrostatic repulsion forces between the protons, and holds the protons and neutrons together. These nuclear forces attract protons to protons, neutrons to neutrons and protons to neutrons.

Questions:

1. In describing his experiment Rutherford said: "It is about as incredible as if you had fired a 350 mm shell at a piece of tissue paper and it came back and hit you". What did Rutherford mean by this statement?

2. A marble (diameter 10 mm) is placed at the center of a football field (length - 100 m). If the marble represents the nucleus of an atom, where would the boundary of the atom be?

NUCLEAR CHEMISTRY
IDENTIFYING NUCLEI

Isotope Notation

Atomic number - the number of protons in the nucleus

Mass number - the number of nucleons (protons plus neutrons) in the nucleus

Isotopes - atoms having the same atomic numbers but different mass numbers (due to a difference in the number of neutrons)

In a neutral atom the number of electrons around the nucleus equals the number of protons in the nucleus. The atomic number determines the identity of the element and the mass number determines the isotope of the element. The number of neutrons in a particular nucleus can be determined by subtracting the atomic number (Z) from the mass number (A). Naturally occurring elements are generally mixtures of two or more isotopes. The molar mass of an element is the mass of one mole of the element containing the isotopes in the percentages found in nature.

The symbol for an isotope is written in the form

mass number ⟶ **A**

X ⟵ element symbol

atomic number ⟶ **Z**

The isotope symbol summarizes basic information about the isotope and is read as the element name followed by the mass number.

Example:

The symbol, $^{238}_{92}U$, is read, ***uranium two-thirty-eight***

Z	=	number of protons	=	atomic number	=	92
A	=	number of nucleons	=	mass number	=	238
N	=	number of neutrons	=	mass number - atomic number		
			=	238 - 92 = 146		

Notes:

1. The molar mass of an isotope is determined on a relative scale which defines the $^{12}_{6}C$ isotope as exactly 12 g/mol.

2. The mass number of an isotope is the nearest whole number of its molar mass.

Table U3
Selected Isotopes

Element	Molar Mass of Element (g/mol)	Common Isotopes	Abundance in Nature (%)	Atomic Number	Mass Number	Subatomic Particles			Application
						Protons	Neutrons	Electrons	
hydrogen	1.01	$^{1}_{1}H$	99.985	1	1	1	0	1	$^{2}_{1}H$ is the isotope of hydrogen found in heavy water, a *moderator* in nuclear reactors.
		$^{2}_{1}H$	0.015	1	2	1	1	1	
carbon	12.0	$^{12}_{6}C$	98.89	6	12	6	6	6	$^{14}_{6}C$ is used in *carbon dating*, a process for determining the age of ancient objects of organic origin.
		$^{13}_{6}C$	1.11	6	13	6	7	6	
		$^{14}_{6}C$	very small	6	14	6	8	6	
oxygen	16.0	$^{16}_{8}O$	99.759	8	16	8	8	8	$^{18}_{8}O$ is used to *tag* or label molecules in the production of radioactive *tracers* for studying the mechanism of chemical reactions.
		$^{17}_{8}O$	0.037	8	17	8	9	8	
		$^{18}_{8}O$	0.204	8	18	8	10	8	
chlorine	35.5	$^{35}_{17}Cl$	75.53	17	35	17	18	17	Illustrates that atomic mass is a *weighted average* of the mass of the isotopes.
		$^{37}_{17}Cl$	24.47	17	37	17	20	17	
cobalt	58.9	$^{59}_{27}Co$	100	27	59	27	32	27	$^{60}_{27}Co$ is used as a source of gamma rays in the treatment of cancer and radiography of metals.
		$^{60}_{27}Co$	very small	27	60	27	33	27	
uranium	238	$^{234}_{92}U$	0.0057	92	234	92	142	92	$^{235}_{92}U$ is the active ingredient in the uranium used in nuclear reactors.
		$^{235}_{92}U$	0.72	92	235	92	143	92	
		$^{238}_{92}U$	99.27	92	238	92	146	92	
neptunium	237	$^{237}_{93}Np$	not found in nature	93	237	93	144	93	$^{237}_{93}Np$ was the first *synthetic element* made from uranium.

Table U4
Structure of Isotopes

Complete Table U4.

	Name	Isotope Notation	Atomic Number	Mass Number	Subatomic Particles			Net Charge on Species
					Protons	Neutrons	Electrons	
	Example 1: helium atom	$^{4}_{2}He$	2	4	2	2	2	0
	Example 2: sodium ion	$^{23}_{11}Na^{+}$	11	23	11	12	10	1+
1.		$^{19}_{9}F$						
2.	zinc atom			65				
3.					19	20	19	
4.					19	21	18	
5.	phosphorus atom					16		
6.		$^{63}_{29}Cu$						
7.	iron atom			56				
8.			92	235				0
9.	uranium atom			238				
10.					12	14	10	
11.	chloride ion					20		
12.	chloride ion			35				
13.		$^{90}_{38}Sr$						
14.					13	14	10	

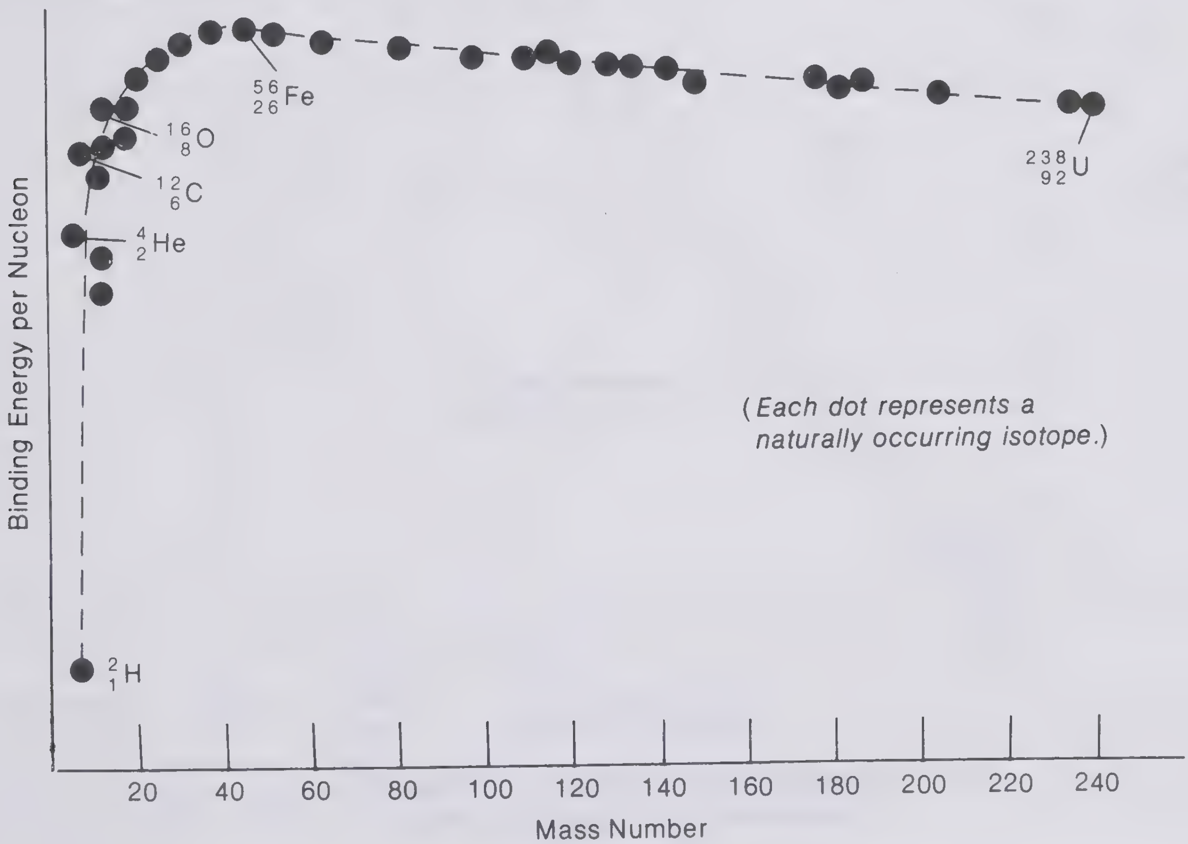
NUCLEAR CHEMISTRY
STABILITY OF NUCLEI

Factors Affecting Nuclear Stability

Numerous experiments have established that the process of radioactivity is associated with the stability of nuclei of atoms. Unstable nuclei tend to undergo a series of spontaneous disintegrations in which nuclei are transmuted (changed) into other nuclei by emission of radiation. It was initially thought that the radioactive atoms contained nuclei too large and complex to be stable. In one respect this is true since *no stable isotope is known with an atomic number greater than 83.* However, since small and simple radioisotopes exist, nuclear size cannot be the only factor that determines nuclear stability. The other factors that influence nuclear stability are the nuclear binding energy, the ratio of neutrons to protons and the odd-even nature of the number of neutrons and protons.

1. Nuclear Binding Energy

For the nucleus to remain intact, the nucleons must be bound together by attractive forces strong enough to overcome the repulsive forces between protons. This binding energy is defined as the energy released when a nucleus is formed from its component nucleons. If the binding energies of the nuclei of naturally occurring isotopes are calculated, it is found that atoms with the lowest and highest mass numbers have the smallest binding energies per nuclear particle. Elements having intermediate mass numbers have the greatest binding energy per nuclear particle. (See Figure U2.)



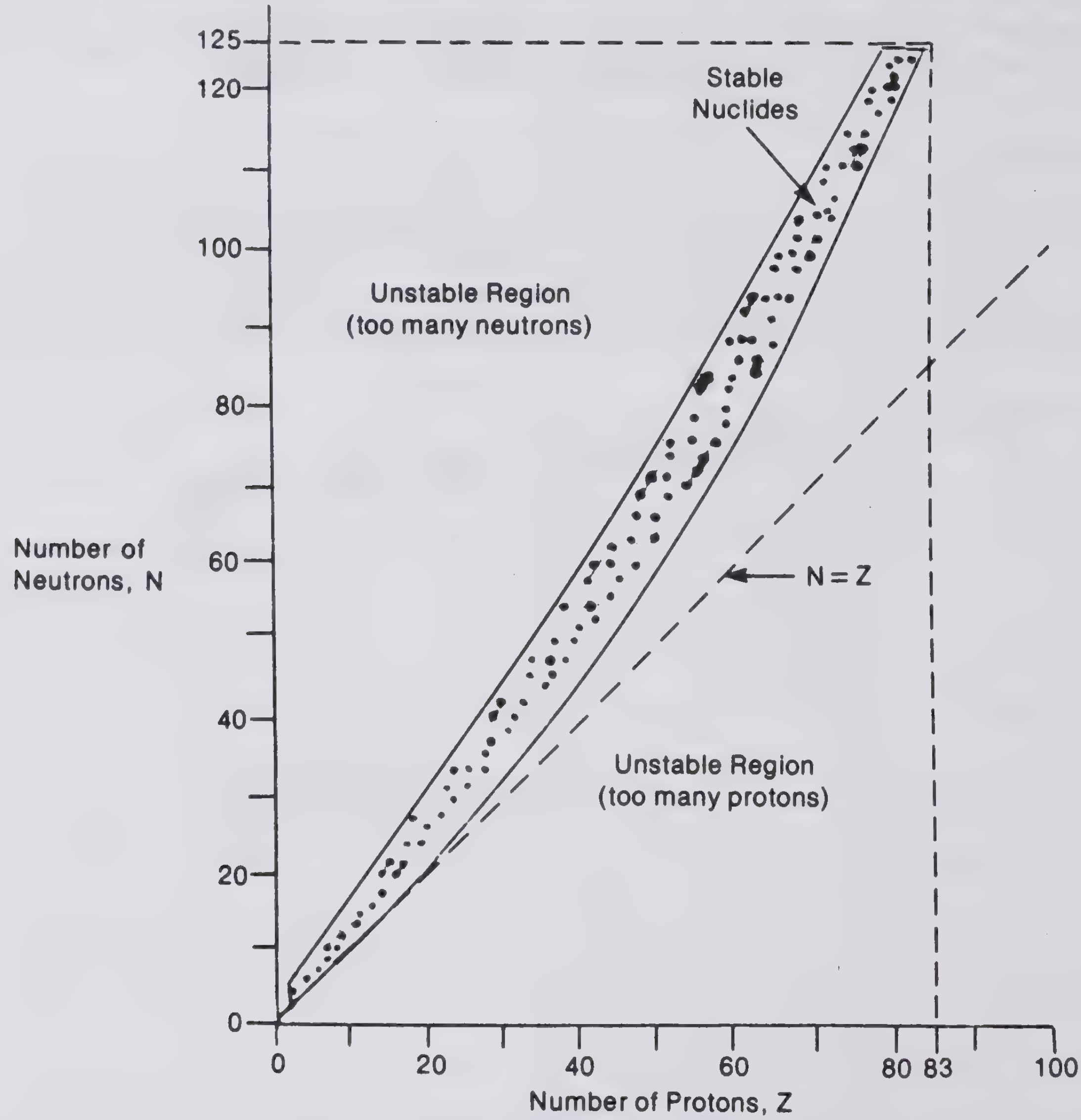
Binding Energy as a Function of Nuclear Mass Number
Figure U2

The elements with the greatest binding energy per nucleon have the most stable nuclei. (The greater the binding energy per nucleon, the more difficult it is to pull the nucleons, and thus the nucleus, apart.) Therefore, it follows that nuclei of elements with the smallest and largest mass number are less stable than nuclei of elements with intermediate mass numbers.

Any nuclear reaction involving an isotope with high binding energy per nucleon is difficult to start because of the large amount of energy required to break the nucleus apart, and is difficult to perpetuate because of the small return on the energy invested. These reactions are analagous to chemical reactions with a large activation energy and a net consumption energy (i.e., endothermic). The difficulty of such reactions results in very few, if any, reactions for these species. Consequently these species are labelled as being stable.

2. Neutron to Proton Ratio

One theory of nuclear structure assumes that nucleons exist in energy levels within the nucleus. In accord with this theory, it can be shown that the most stable nuclei, and hence nuclei in which nucleons occupy the lowest energy level, are those with certain neutron-proton combinations. This becomes apparent when the number of neutrons is plotted versus the number of protons for the known stable isotopes. (See Figure U3.)



Number of Neutrons as a Function of Number of Protons in Stable Nuclei
Figure U3

Several facts can be derived from analysis of the plot of number of neutrons versus the number of protons.

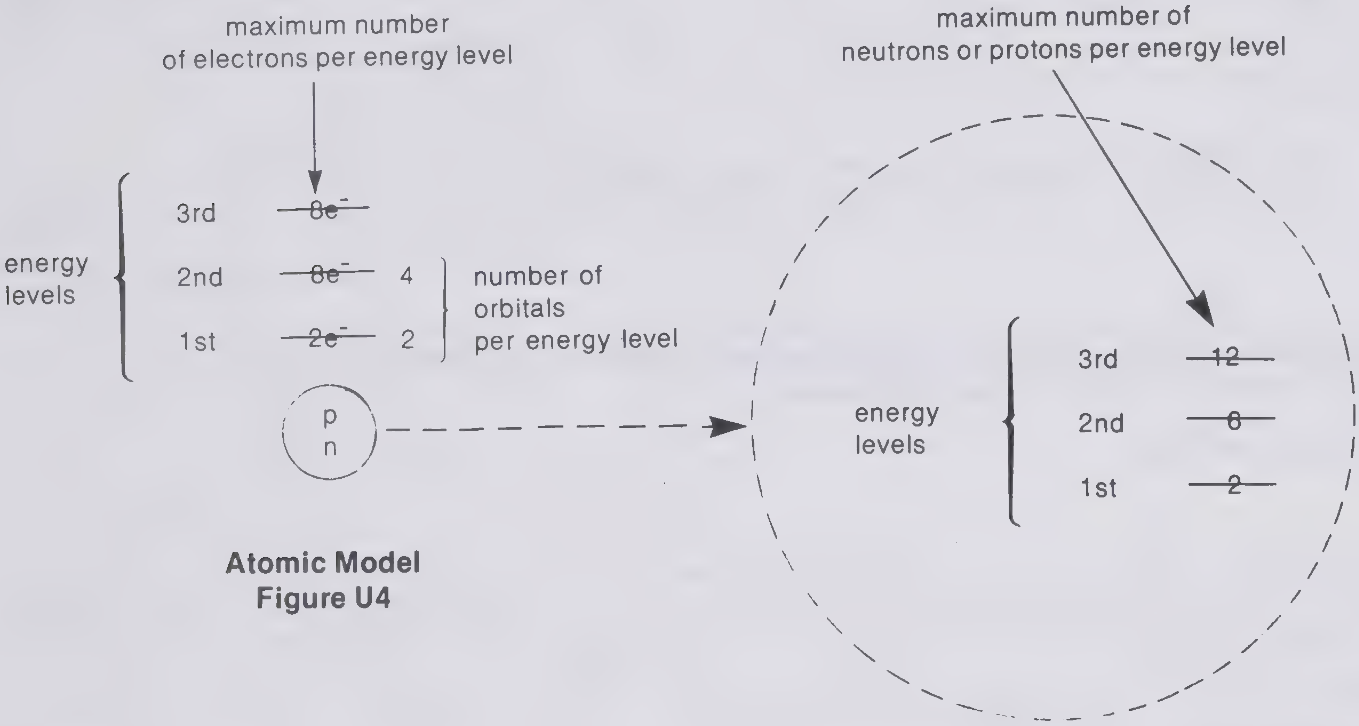
1. Stable nuclei are confined into a narrow zone indicating that the neutron-to-proton (n/p) ratio required for stability is relatively restricted.
2. The n/p ratio of stable nuclei increases with an increase in the number of protons. The stable isotopes of Elements 1 to 20 have a n/p ratio of 1 or greater, while stable isotopes of elements 21 to 82 all have n/p ratios greater than 1. Thus, the greater the number of protons in a nucleus, the greater the number of neutrons per proton required to form a stable nucleus.
3. Elements with more than 83 protons can form no stable nuclei. Thus, no stable nucleus with more than 83 protons can form regardless of the number of neutrons. It appears that nuclear forces cannot permanently exceed repulsive forces when more than 83 protons are assembled.

NUCLEAR CHEMISTRY
STABILITY OF NUCLEI

3. Odd-Even Nature

The odd-even nature of the number of neutrons and protons has some effect upon the stability of nuclei. The greatest number of stable nuclei have an even number of both protons and neutrons. Of lesser frequency are stable nuclei with an even number of protons and an odd number of neutrons or vice-versa. Only a few stable nuclei are known with an odd number of both protons and neutrons.

The energy level model for nuclear stability (Figure U5) can account for the odd-even nature of the number of nucleons affecting the nuclear stability. This model is analogous to the atomic model of electron energy levels (Figure U4).



Atomic Model
Figure U4

Nuclear Model
Figure U5

In the atomic model each orbital can hold a maximum of two electrons before it is filled. Complete or filled energy levels (e.g., noble gases) have even numbers of electrons and result in a very stable arrangement.

In the analogous nuclear model, filled nucleon energy levels with even numbers of nucleons result in a very stable arrangement. This model also suggests that there are separate levels for protons and neutrons (i.e., an odd number of protons and an odd number of neutrons results in an even number of nucleons but an unstable nucleus). An alpha particle ($Z = 2$, $N = 2$) is very stable and it is not surprising then that many radioactive nuclei emit alpha particles.

Examples:

The *mass numbers* of all known isotopes of Ca, K, Mg, Al and Si are listed below. Note that, if Z is even, an even mass number means an even number of neutrons, and, if Z is odd, an odd mass number means an even number of neutrons.

$_{20}Ca$	stable	40,42,43,44,46,48
	unstable	37,38,39,41,45,47,49,50
$_{19}K$	stable	39,41
	unstable	36,37,38,40,42,43,44,45,46,47
$_{12}Mg$	stable	24,25,26
	unstable	21,22,23,27,28,29,30
$_{13}Al$	stable	27
	unstable	23,24,25,26,28,29,30,31,32,33
$_{14}Si$	stable	28,29,30
	unstable	25,26,27,31,32,33,34,35,36

<u>Note:</u>

Generally, if Z is odd (i.e., Al) there are less stable isotopes compared to Z being even (i.e., Ca).

NUCLEAR CHEMISTRY
STABILITY OF NUCLEI

1. Define nuclear binding energy.

2. How is the binding energy per nucleon related to nuclear stability?

3. What is the relationship between mass number and nuclear stability.

4. Based on Figure U3, identify three types of unstable nuclei.

Using the n/p ratio (Figure U3) and the odd-even nature predict and circle the more unstable isotope for each pair of isotopes listed below. Explain each answer.

5. $^{202}_{80}Hg$ and $^{202}_{85}At$

6. $^{146}_{55}Cs$ and $^{146}_{54}Xe$

7. $^{22}_{10}Ne$ and $^{212}_{86}Rn$

8. $^{39}_{20}Ca$ and $^{40}_{20}Ca$

9. Write *e-e*, *e-o*, *o-e* and *o-o* above each mass number in the example on the previous page to indicate *even* or *odd* numbers of protons and neutrons respectively. What generalization can be made?

10. Why does calcium have a relatively large number of stable isotopes?

11. The nuclear model (Figure U5) is not the only model that has been proposed. What are the important criteria for an acceptable model?

NUCLEAR CHEMISTRY
NUCLEAR EQUATIONS

Nuclear Equations

Nuclear reactions, like chemical reactions, can be readily represented by equations. However, equations for nuclear reactions, unlike those for chemical reactions, use symbols that always include the atomic number and the mass number. A nuclear equation is balanced when the sum of the atomic numbers on the left side is equal to the sum on the right side, and the sum of the mass numbers on the left side equals the sum on the right side. In other words, nucleons are conserved in nuclear reactions. Note that the atomic number identifies the nucleus or particle and the mass number gives the specific isotope of an atom.

Nuclear reactions, unlike chemical reactions, are generally not concerned with the orbital electrons present. Hence, charge balance (due to electronic charge not nuclear charge) is not considered.

Example 1: Alpha Decay

$$^{222}_{86}Rn \longrightarrow \underbrace{^{218}_{84}Po}_{\text{product nucleus is predicted from atomic number}} + {}^{4}_{2}\alpha$$

sum of mass numbers is 222 for reactants and products

sum of atomic numbers is 86 on both sides of the equation

One type of radioactivity (see Page U2) involves the emission of a beta-negative particle. This high energy electron is a product of the decay of a neutron and is not an orbital electron.

Example 2: Beta Decay

$$^{228}_{90}Th \longrightarrow {}^{228}_{91}Pa + {}^{0}_{-1}\beta$$

N = 138   N = 138

Z = 90   Z = 91

$$^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta$$

Emission of a beta-negative particle gives a new nucleus with an extra proton and one less neutron. The mass number remains constant.

Example 3: Gamma Emission

Gamma rays (see Table U1) may be absorbed or emitted by a nucleus. This may simply change the energy state of a nucleus (e.g., no nuclear reaction) or, as in many radioactive changes, gamma rays may be emitted along with alpha or beta particles.

$$^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha + \gamma$$

Note that gamma radiation does not result in a change of total mass or atomic number

Exercise:

Complete the following nuclear equations.

1. $^{236}_{93}Np \longrightarrow$ __________ $+ {}^{236}_{94}Pu$
2. $^{210}_{83}Bi \longrightarrow {}^{4}_{2}\alpha +$ __________
3. $^{14}_{7}N + {}^{4}_{2}\alpha \longrightarrow$ __________ $+ {}^{1}_{1}H$
4. $^{12}_{6}C + {}^{1}_{0}n \longrightarrow 2{}^{1}_{0}n +$ __________
5. $^{210}_{82}Pb \longrightarrow {}^{210}_{83}Bi +$ __________ $+ \gamma$
6. $^{53}_{26}Fe \longrightarrow {}^{0}_{1}\beta +$ __________ $+ \gamma$
7. __________ $+ {}^{11}_{5}B \longrightarrow {}^{257}_{103}Lr + 4{}^{1}_{0}n$
8. $^{2}_{1}H +$ __________ $\longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$
9. __________ $\longrightarrow {}^{4}_{2}\alpha + {}^{222}_{86}Rn + \gamma$
10. $^{103}_{44}Ru \longrightarrow {}^{103}_{45}Pd + {}^{0}_{-1}\beta +$ __________
11. __________ $+ {}^{1}_{0}n \longrightarrow 3{}^{1}_{0}n + {}^{92}_{36}Kr \quad {}^{141}_{56}Ba$

NUCLEAR CHEMISTRY
NUCLEAR REACTION TYPES

Nuclear Reaction Types

Depending upon reaction conditions and stability of nuclei, four main types of nuclear reactions can be identified.

1. Radioactivity Decay

$$\text{nucleus} \longrightarrow \text{nucleus} + \left\{ \begin{array}{c} \text{alpha} \\ \text{or} \\ \text{beta} \\ \text{particle} \end{array} \right\}$$

This reaction is actually a *natural transmutation*. Atoms with naturally occurring unstable nuclei disintegrate to form a different element (which may also be radioactive). Radioactive decay may be further classified according to the type of radiation given off. Gamma radiation is also often produced by this decay.

Example 1: $^{222}_{86}Rn \longrightarrow {}^{218}_{84}Po + {}^{4}_{2}\alpha$ (alpha decay)

Example 2: $^{228}_{90}Th \longrightarrow {}^{228}_{91}Pa + {}^{0}_{-1}\beta$ (beta-negative decay)

Example 3: $^{65}_{30}Zn \longrightarrow {}^{65}_{29}Cu + {}^{0}_{1}\beta$ (beta-positive or positron decay)

Beta-negative decay results from $^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{1}\beta$ and is followed by the almost instantaneous annihilation of the positron as it collides with an electron $^{0}_{1}\beta + {}^{0}_{-1}e \longrightarrow \gamma + \gamma$

2. Artificial Transmutation

$$\text{nucleus} + \begin{array}{c} \text{small} \\ \text{particle} \\ \text{or nucleus} \end{array} \longrightarrow \text{nucleus} + \begin{array}{c} \text{neutron(s)} \\ \text{(may also be a proton)} \end{array}$$

By bombarding a nucleus with small particles (alpha, beta, neutrons, protons, light nuclei, etc.) one new element is produced. The transuranium elements have been produced by artificial transmutations.

Example: $^{238}_{92}U + {}^{2}_{1}H \longrightarrow {}^{238}_{93}Np + 2\,{}^{1}_{0}n$

3. Fission

$$\begin{array}{c} \text{heavy} \\ \text{nucleus} \end{array} + \text{neutron} \longrightarrow \begin{array}{c} \text{lighter} \\ \text{nucleus} \end{array} + \begin{array}{c} \text{lighter} \\ \text{nucleus} \end{array} + \text{neutron(s)} + \text{energy}$$

The heavy nucleus (mass number greater than 56) is split into two lighter nuclei of approximately equal size (usually by a neutron).

Example: $^{239}_{94}Pu + {}^{1}_{0}n \longrightarrow {}^{106}_{44}Ru + {}^{131}_{50}Sn + 3\,{}^{1}_{0}n + \text{energy}$

4. Fusion

$$\begin{array}{c} \text{light} \\ \text{nucleus} \end{array} + \begin{array}{c} \text{light} \\ \text{nucleus} \end{array} \longrightarrow \begin{array}{c} \text{heavier} \\ \text{nucleus} \end{array} + \begin{array}{c} \text{small} \\ \text{particle} \end{array} + \text{energy}$$

Two light nuclei (same or different but with mass numbers less than 56) fuse together to form a heavier nucleus.

Example: $^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$

Exercise:

Identify the reaction type beside each equation in the exercise on Page U13.

NUCLEAR CHEMISTRY
RADIOACTIVE DECAY

1. Radioactive Decay

Atoms with naturally occurring unstable nuclei undergo radioactive decay emitting an alpha or beta particle and gamma rays to form a slightly lighter and/or more stable nucleus. This decay can produce new atoms of new elements which may themselves be radioactive and hence undergo further disintegration. Naturally occurring radioactive elements with atomic numbers above lead fall into three orderly disintegration series. Each series progresses from one element to the next by a loss of either an alpha or beta particle, finally ending in a nonradioactive form of lead. The Uranium Series starts with $^{238}_{92}U$ and ends with $^{208}_{82}Pb$. The Thorium Series starts with $^{232}_{90}Th$ and ends with $^{208}_{82}Pb$. The Actinium Series starts with $^{235}_{92}U$ and ends with $^{207}_{82}Pb$.

Theory of Beta Decay

It is customary in elementary models of a nucleus to consider protons and neutrons as fundamental particles and *basic building blocks* of a nucleus. In alpha decay the radioactive nucleus loses a particle containing two protons and two neutrons. In beta decay, the radioactive nucleus loses either an electron or a positron. To account for beta decay and other experimental evidence, protons and neutrons *cannot* be considered as fundamental particles.

In the beta-negative decay of strontium-90,

$$^{90}_{38}Sr \longrightarrow {}^{90}_{39}Y + {}^{0}_{-1}\beta$$

one of the neutrons in the strontium nucleus must be converted to a proton and an electron (which is ejected). This is represented as

$$^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}\beta$$

For a beta-positive decay, such as,

$$^{13}_{7}N \longrightarrow {}^{13}_{6}C + {}^{0}_{1}\beta$$

one of the protons is converted to a neutron and a positron.

$$^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{1}\beta$$

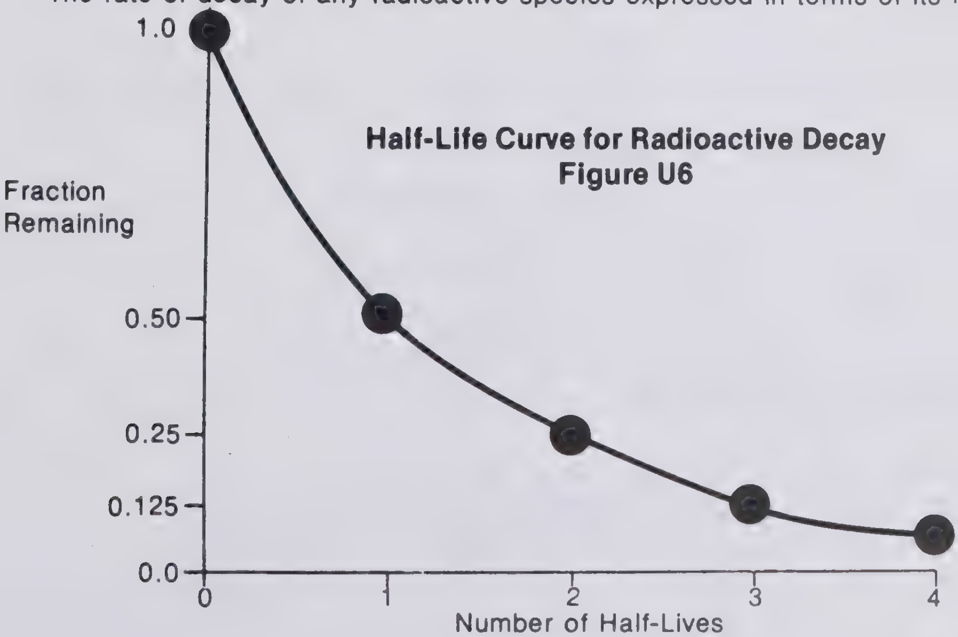
Half-Life

Each radioactive isotope disintegrates at a specific and constant rate which is expressed in terms of half-life. The *half-life* is the time required for one-half of the nuclei in a given sample of the isotope to disintegrate. Half-life is usually designated as $t_{1/2}$ and can be taken as a measure of the stability of the nucleus. For example, the equation,

$$^{222}_{86}Rn \longrightarrow {}^{218}_{84}Po + {}^{4}_{2}\alpha \qquad t_{1/2} = 3.8\ d$$

shows that the alpha decay of $^{222}_{86}Rn$ has a half-life of 3.8 d. Consider a sample containing 1000 atoms of $^{222}_{86}Rn$ initially. After 3.8 d, 500 atoms of $^{222}_{86}Rn$ will remain; after another 3.8 d period there will be 250 atoms of $^{222}_{86}Rn$ left. This process continues until practically all of the $^{222}_{86}Rn$ has disintegrated.

The rate of decay of any radioactive species expressed in terms of its half-life is shown in Figure U6.

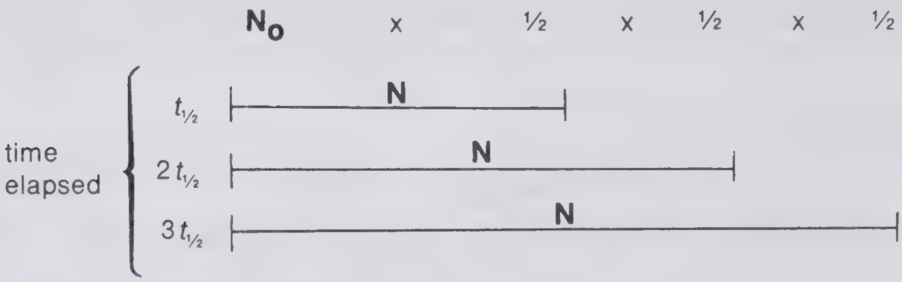


Half-Life Curve for Radioactive Decay
Figure U6

NUCLEAR CHEMISTRY
RADIOACTIVE DECAY

Since the rate of radioactive decay is not affected by changes in temperature or chemical bonding, the half-life of a particular radioactive isotope is a constant value. The longer the half-life, the more stable the nucleus. A half-life greater than 100 Ga is not detectable.

The number of isotopes remaining (N) depends on the initial number of isotopes (N_o) and the time that has elapsed in terms of half-lives.



Therefore, the radioactive decay law as a mathematical formula becomes

$$N = N_o(\tfrac{1}{2})^n$$

$$m = m_o(\tfrac{1}{2})^n$$
$$n = n_o(\tfrac{1}{2})^n$$

where

N = number of atoms

m = mass

n = number of moles

where the exponential n is the number of half-lives elapsed

$$\left(n = \frac{\text{time elapsed}}{\text{half-life}} \right)$$

or $n = \dfrac{t}{t_{1/2}}$

Note: Use the y^x key on a calculator for obtainding $(\tfrac{1}{2})^n$ where n is a fractional value.

Example:

If a certain sample initially contains 6.4×10^{10} atoms of $^{24}_{11}Na$, determine the number of $^{24}_{11}Na$ atoms which will remain after 60 h. Given,

$$^{24}_{11}Na \longrightarrow \,^{24}_{12}Mg + \,^{0}_{1-}\beta \qquad t_{1/2} = 15\ h$$

$$n = \frac{t}{t_{1/2}} = \frac{60\ h}{15\ h} = 4.0$$

$$N = N_o(\tfrac{1}{2})^n$$
$$= 6.4 \times 10^{10} \text{ atoms } (\tfrac{1}{2})^{4.0}$$
$$= 6.4 \times 10^{10} \text{ atoms} \times \frac{1}{16}$$
$$= 4.0 \times 10^{9} \text{ atoms}$$

After 60 h, 4.0×10^9 atoms of $^{24}_{11}Na$ will remain in the sample.

NUCLEAR CHEMISTRY
RADIOACTIVE DECAY

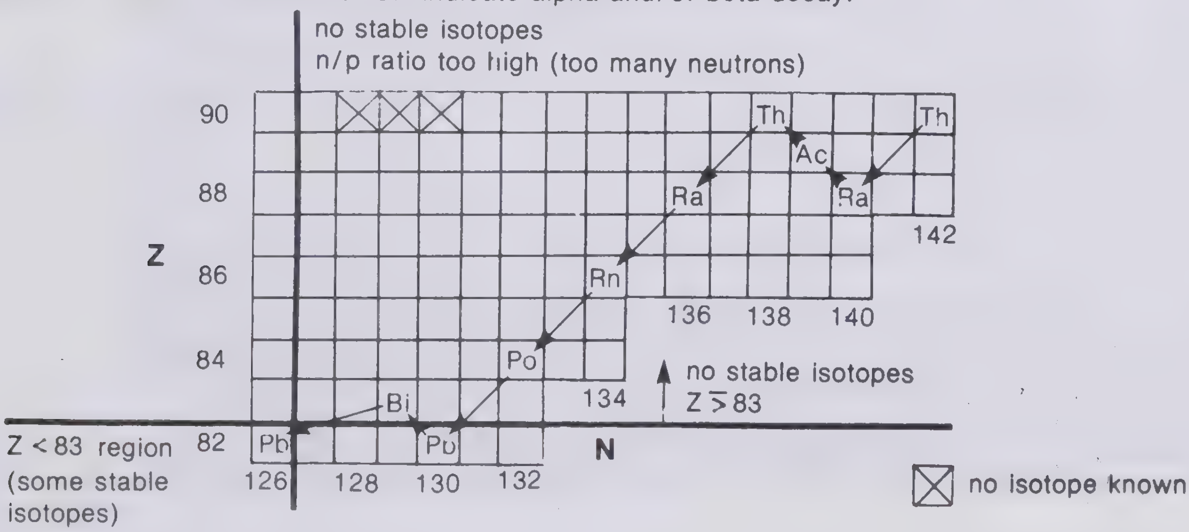
Exercise

The transmutation of $^{232}_{90}Th$ to $^{208}_{82}Pb$ is an example of a radioactive element that undergoes an orderly disintegration series. Table U5 lists the successive decay products in this series. Complete Table U5 by using the ALCHEM data sheet to find the decay modes and half-lives of each of the intermediate isotopes. All of the isotopes except the last ($^{212}_{83}Bi$) emit gamma radiation in addition to alpha and/or beta radiation.

Table U5
Radioactive Decay Series for $^{232}_{90}Th$ (Thorium Series)

	Isotope	Radioactive Decay	Half-Life
e.g.	$^{232}_{90}Th$	$^{232}_{90}Th \longrightarrow\ ^{228}_{88}Ra + ^{4}_{2}\alpha + \gamma$	$t_{1/2} = 1.4 \times 10^{10}$ a
1.	$^{228}_{88}Ra$		
2.	$^{228}_{89}Ac$		
3.	$^{228}_{90}Th$		
4.	$^{224}_{88}Ra$		
5.	$^{220}_{86}Rn$		
6.	$^{216}_{84}Po$		
7.	$^{212}_{82}Pb$		
8.	$^{212}_{83}Bi$		
	$^{208}_{82}Pb$	stable, no futher decay	not detectable (> **100 Ga)**

Use Table U5 to add the mass number and the atomic number to each of the isotopes symbols in the Thorium 232 series nuclide chart below. Over each arrow indicate alpha and/or beta decay.



NUCLEAR CHEMISTRY
RADIOACTIVE DECAY

9. Which of the isotopes in the transformation of $^{232}_{90}Th$ to $^{208}_{82}Pb$ is most stable? Which is least stable?

10. Some text sources list $^{212}_{83}Bi$ as undergoing beta-negative decay to produce an unstable intermediate nucleus with a half-life of 10^{-7} s, which then decays to $^{208}_{82}Pb$. What is the postulated intermediate?

11. If a given mineral sample contains 3.2×10^6 atoms of $^{232}_{90}Th$, how many of these will remain after 5.6×10^{10} a?

12. A certain sample contains 6.4×10^{20} atoms of $^{90}_{38}Sr$. How many atoms will remain after 84 a?

13. If a vial initially contains 10.0 mmol of $^{131}_{53}I$ how many moles of $^{131}_{53}I$ will reamin after 48.3 d?

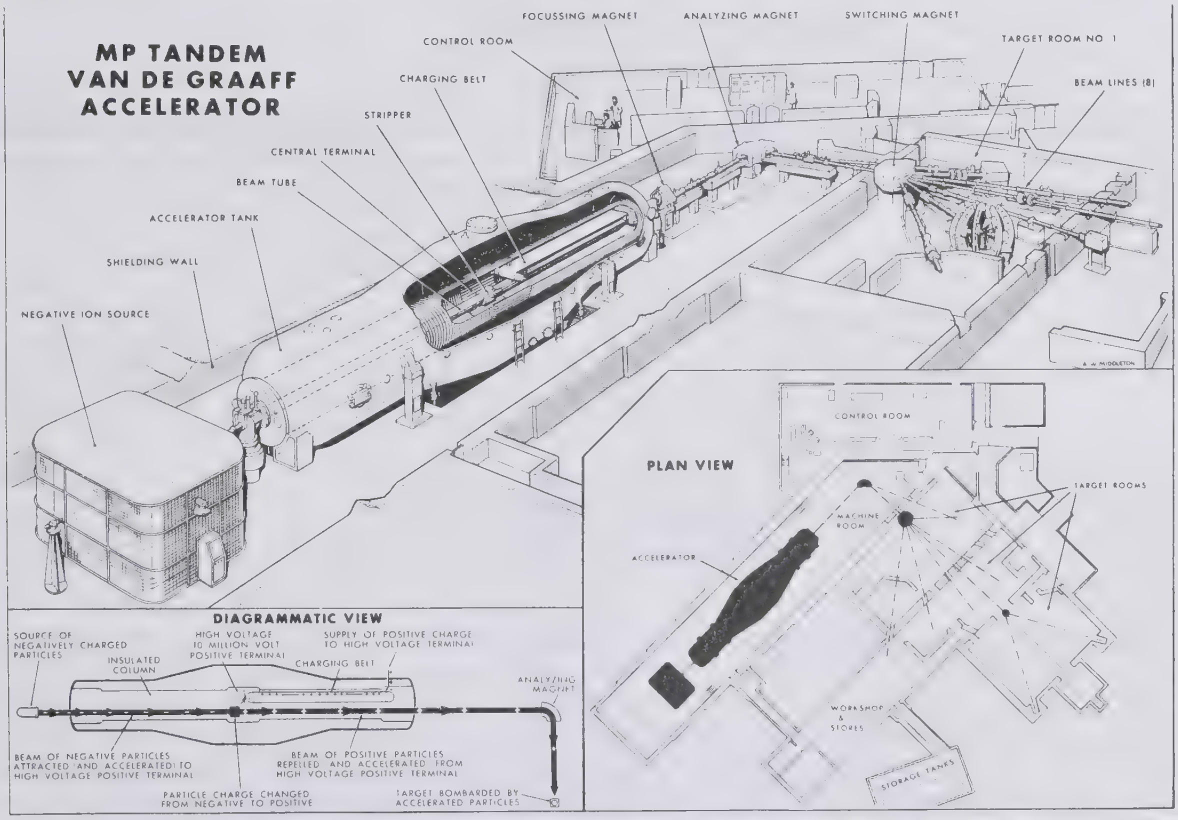
14. Two days after it was prepared a sample of $^{242}_{95}Am$ has a mass of 4.53 µg. What was the original mass of the sample?

2. Artificial Transmutation

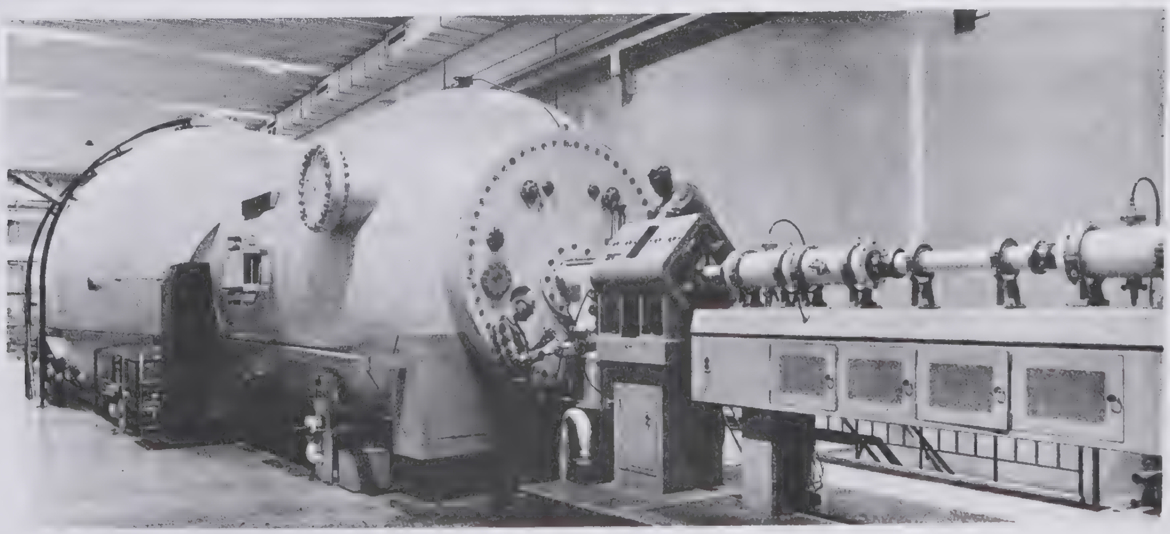
Not long after the discovery of natural radioactivity that resulted in natural transmutations, scientists attempted to transmute atoms artificially by bombarding them with alpha particles, neutrons, protons, deuterons (^2_1H), electrons, etc. (*Transmutation* is the conversion of one element into another.) The first artificial transmutation was achieved by Ernest Rutherford in 1919. He succeeded in bombarding the nuclei of nitrogen atoms with alpha particles to produce an isotope of oxygen according to the following equation.

$$^{14}_{7}N \;+\; ^{4}_{2}\alpha \longrightarrow ^{17}_{8}O \;+\; ^{1}_{1}p$$

Rutherford's experiment opened the door to nuclear transmutations of all kinds. Massive instruments were developed to accelerate charged particles to very high speeds and energies to aid their penetration of the nucleus. In some transmutations, artificial radioactive isotopes were produced. These artificial radioactive isotopes behave like natural radioactive isotopes in that they disintegrate in a definite manner and have a specific half-life. The transuranium elements (atomic number >92) are not found in nature and have all been prepared by artificial transmutation.

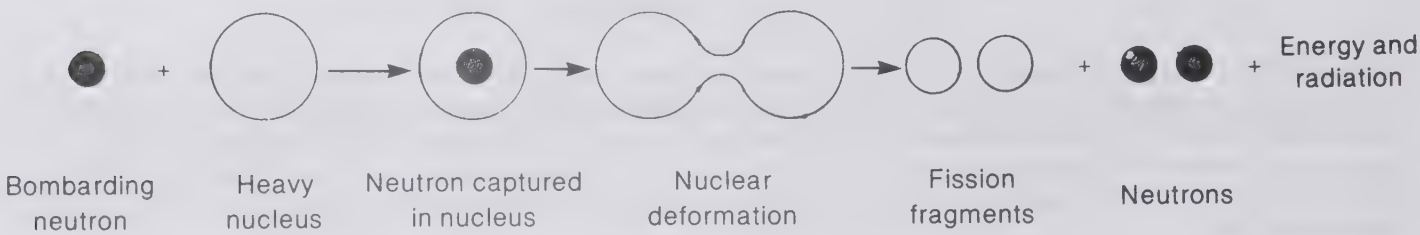


The MP tandem accelerator at Chalk River. This "atom smasher" directs particles at speeds up to 64 Mm/s (0.2 c) toward target material.



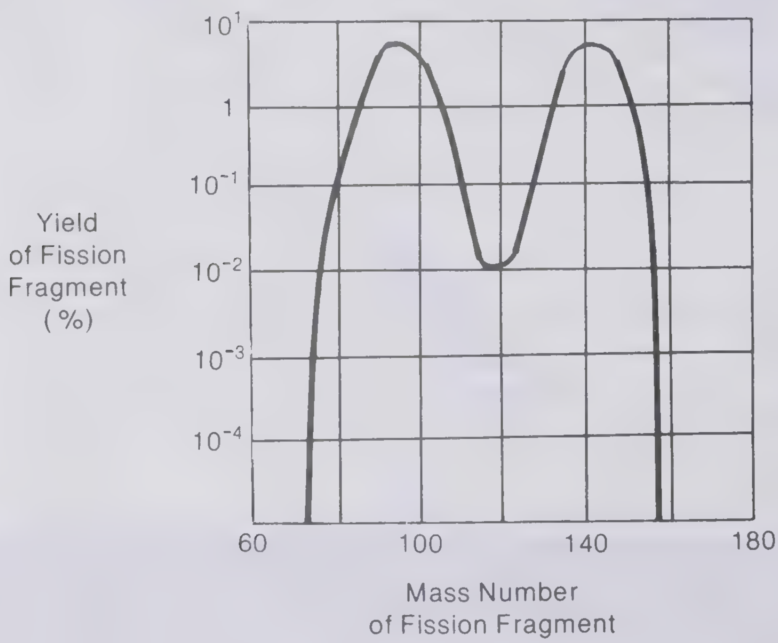
3. Nuclear Fission

The bombardment of large nuclei with neutrons resulting in a reaction where the nucleus splits into two smaller nuclei of approximately similar mass is known as *nuclear fission*. Neutrons, being uncharged particles, are ideal for nuclear bombardment since they can readily penetrate positively charged nuclei. Nuclear fission is also accompanied by the release of various radiations and enormous quantities of energy. The process by which nuclear fission takes place is illustrated in Figure U7.



The Nuclear Fission Process
Figure U7

The best known example of nuclear fission is that which occurs when the isotope uranium-235 is bombarded with neutrons. Nuclear fission, such as that of uranium-235, is very complex. The fission of uranium can occur in many ways and produce a variety of product nuclei, as shown in Figure U8.



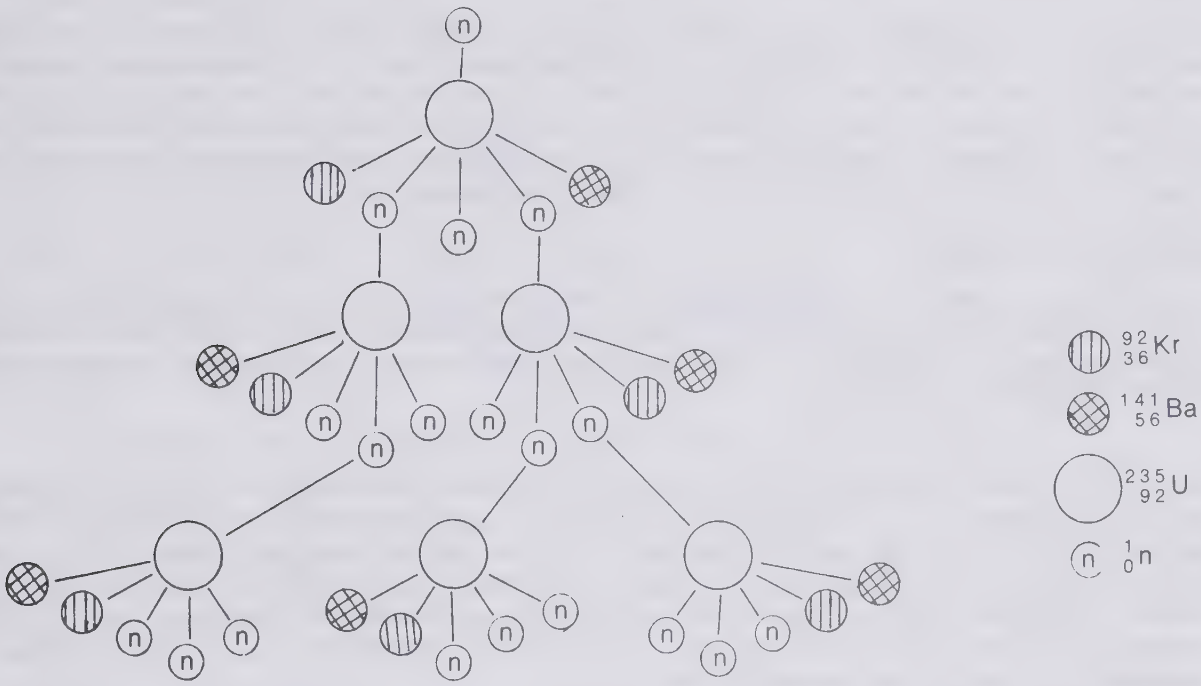
Fission Products for Uranium-235
Figure U8

NUCLEAR CHEMISTRY
NUCLEAR REACTIONS

The following equation may be taken as a typical reaction which occurs when an uranium-235 atom undergoes fission to produce two possible fragments.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + 1.9 \times 10^{10} \text{ kJ}$$

Each fission of $^{235}_{92}U$ produces three neutrons, which in turn can be captured by other $^{235}_{92}U$ nuclei thereby continuing the process to give a *chain reaction*. The chain reaction process is illustrated in Figure U9.



Typical Chain Reaction for Uranium-235
Figure U9

Because nuclear fission is a self-sustaining chain reaction accompanied by the release of *enormous* quantities of energy, it can be used in nuclear reactors to product heat energy or in the manufacture of atomic bombs. Both nuclear reactors and atomic bombs operate on the principle that a certain minimum mass of fissionable material, called *critical mass*, is needed before a fission reaction is sustained. The critical mass must be such that the fission produces sufficient neutrons to compensate for neutrons that escape and are lost. If only one of the neutrons produced by a fission reacted with another uranium-235 atom, the process would continue at a constant rate. At this condition, the process would be described as critical and would occur when a critical mass of fissionable material was assembled. The operation of a nuclear reactor would require that the fission is maintained at the critical level. If more than one neutron caused additional fissions (see Figure U9), the process would result in an expanding chain reaction creating a supercritical situation that would lead to an explosion. Thus, for atomic bombs, the major requirement is a supercritical mass of fissionable material. Fissionable materials, which are highly enriched (greater than 90%) and stored in two or more seperate units can be brought together to produce a supercritical mass and hence an explosion. These types of bombs were denotated in Japan near the end of World War II over Hiroshima (U-235 fission) and Nagasaki (Pu-239 fission).

4. Nuclear Fusion

The process in which nuclei of two lighter elements are united to form a heavier nucleus is known as *nuclear fusion.*

$$^{2}_{1}H \quad + \quad ^{3}_{1}H \longrightarrow \, ^{4}_{2}He \quad + \quad ^{1}_{0}n \quad + \quad 1.7 \times 10^{9}\ kJ$$

Fusion reactions require temperatures around a million degrees Celsius and enormous pressures. Under such conditions all elements are in the gaseous form and atoms cannot be combined to form molecules. Most of the atoms are completely ionized - all of the electrons removed. These electrons freed from their parent atoms, become part of the gas itself, moving about as individual particles. This form of matter is called a *plasma.* The symbols in the above equation and other fusion equations therefore refer to the nuclei and not the neutral atoms.

The energy output of fusion reactions is even greater than that of fission reactions. Only about 0.1 percent of the mass involved in fission reactions is converted into energy whereas in fusion reactions between 0.4 and 0.7 percent of the mass is converted into energy. Thus on the basis of mass, fusion reactions produce four to seven times as much energy as fission reactions. To appreciate the magnitude of energy produced by fusion reactions consider that one gram of hydrogen undergoing fusion to produce helium produces heat that would require 20 Mg of coal. (One gram of uranium undergoing fission is equivalent to 3 Mg of coal.)

Applications of Nuclear Fusion

The fusion reaction is the basis for the thermonuclear or hydrogen bomb. Since fusion reactions require high temperatures to get started, a fission bomb is used to start the fusion reaction in the hydrogen bomb. There are many well-known reactions that may be used for hydrogen bomb explosions. A typical one that releases a lot of energy is shown in the following equation.

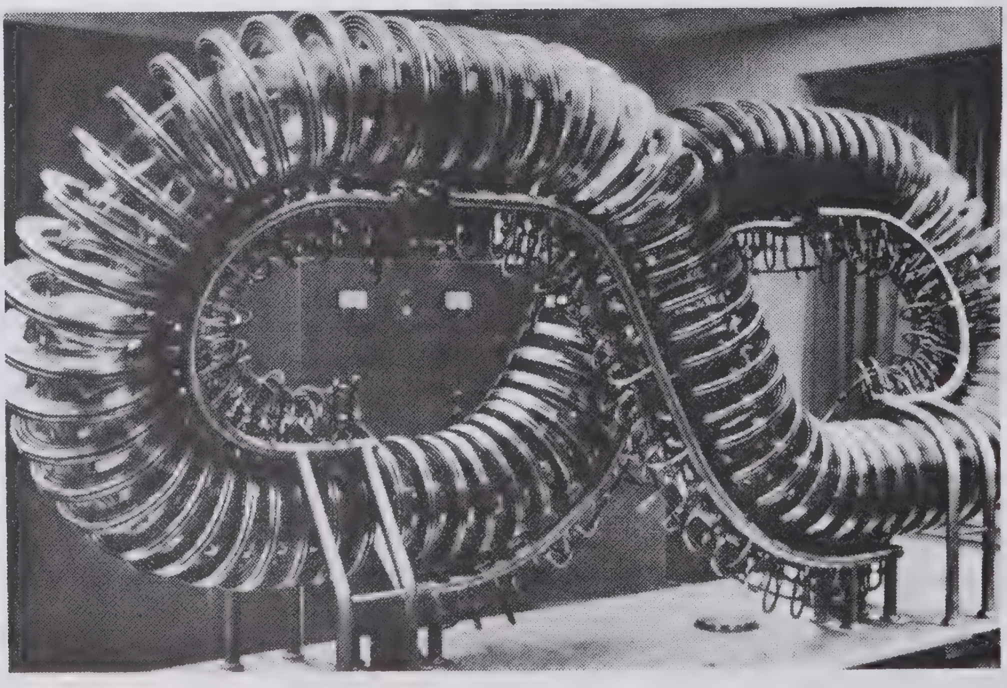
$$^{6}_{3}Li \quad + \quad ^{2}_{1}H \longrightarrow 2\,^{4}_{2}He \quad + \quad 2.2 \times 10^{9}\ kJ$$

In principle, fusion reactions might be used as a source of controlled nuclear energy. However, temperatures required to start fusion reactions and the temperatures created by fusion reactions are so high that no known substance has been found that could be used as a container. To achieve a controlled fusion reaction, the plasma, at temperatures of millions of degrees, must be contained in such a way that it does not contact the walls of the container. Work is being done on using magnetic fields to hold the high temperature reactants away from the walls of a container. When problems of controlled fusion are finally solved, the unlimited supply of hydrogen in the oceans promises an almost endless source of energy.

The application of nuclear fusion as a controlled energy source does involve problems with radioactive wastes. Experimentally, a controlled fusion reaction has not yet been accomplished and therefore the extent of the radioactive waste problem is difficult to predict. Certainly large quantities of tritium ($^{3}_{1}H$), which is radioactive ($^{0}_{-1}\beta$ decay, $t_{1/2}$ = 12.3 a), will be produced. In addition, the bombardment of high energy neutrons on the reactor walls will not only make them radioactive, but also result in physical damage. The replacement of the walls (perhaps every five years) and the disposal of the tritium may create serious radioactive waste disposal problems.

Stellarator

(an experimental fusion device in use at Princeton, New Jersey).



NUCLEAR CHEMISTRY
NUCLEAR REACTIONS

For each of the following equations determine the missing product. Classify the reactions as radioactive decay, artificial transmutation, fission or fusion.

Isotopes of uranium and plutonium can split in a variety of ways as the following examples illustrate.

Reaction Type

1. $^{235}_{92}U + ^{1}_{0}n \longrightarrow 2^{1}_{0}n + ^{137}_{52}Te +$ __________ ________________
2. $^{241}_{94}Pu \longrightarrow ^{237}_{93}Np + ^{0}_{1-}\beta +$ __________ ________________
3. $^{235}_{92}U \longrightarrow ^{231}_{90}Th +$ __________ ________________
4. $^{239}_{94}Pu + ^{1}_{0}n \longrightarrow 3^{1}_{0}n + ^{90}_{36}Kr +$ __________ ________________
5. $^{237}_{92}U \longrightarrow ^{237}_{93}Np +$ __________ ________________
6. $^{235}_{92}U + ^{1}_{0}n \longrightarrow 2^{1}_{0}n + ^{0}_{1-}\beta + ^{95}_{42}Mo +$ __________ ________________

Nuclear reactions are the source of energy in the stars. The following are some examples of stellar reactions.

Reaction Type

7. $4^{1}_{1}H \longrightarrow ^{4}_{2}He +$ __________ ________________
8. $3^{4}_{2}He \longrightarrow$ __________ ________________
9. $^{114}_{48}Cd + ^{1}_{0}n \longrightarrow$ __________ ________________
10. $^{115}_{48}Cd \longrightarrow ^{0}_{1-}\beta +$ __________ ________________
11. $^{114}_{48}Cd + ^{1}_{1}p \longrightarrow$ __________ ________________

Elements whose atomic numbers are greater than 92 (transuranium elements) do not occur in nature. Elements 93 through 104 have been prepared by the following bombardment reactions.

Reaction Type

12. $^{238}_{92}U + ^{2}_{1}H \longrightarrow 2^{1}_{0}n +$ __________ ________________
13. $^{238}_{92}U + ^{4}_{2}\alpha \longrightarrow 3^{1}_{0}n +$ __________ ________________
14. $^{239}_{94}Pu + ^{4}_{2}\alpha \longrightarrow ^{242}_{96}Cm +$ __________ ________________
15. $^{244}_{96}Cm + ^{4}_{2}\alpha \longrightarrow$ __________ $+ ^{1}_{1}p + 2^{1}_{0}n$ ________________
16. $^{238}_{92}U + ^{12}_{6}C \longrightarrow ^{246}_{98}Cf +$ __________ ________________
17. $^{238}_{92}U + ^{14}_{7}N \longrightarrow ^{247}_{99}Es +$ __________ ________________
18. $^{238}_{92}U + ^{16}_{8}O \longrightarrow 5^{1}_{0}n +$ __________ ________________
19. $^{253}_{99}Es + ^{4}_{2}\alpha \longrightarrow ^{1}_{0}n +$ __________ ________________
20. $^{246}_{96}Cm + ^{13}_{6}C \longrightarrow ^{254}_{102}No +$ __________ ________________
21. $^{249}_{98}Cf + ^{12}_{6}C \longrightarrow ^{257}_{104}Ku +$ __________ ________________

NUCLEAR CHEMISTRY
NUCLEAR REACTIONS

22. Distinguish between nuclear fission and nuclear fusion.

23. Compare the suitability of alpha particles and neutrons for nuclear bombardment.

24. Discuss the process of nuclear fission. Relate the process to critical mass. What may happen if the mass is supercritical?

25. Explain the problems associated with using nuclear fusion reactions as a source of controlled nuclear energy.

26. Why would nuclear fusion be a more desireable source of energy than nuclear fission?

What nuclear processes are used to form the following species in stars?

27. helium

28. nuclei up to $^{56}_{26}Fe$

29. nuclei beyond $^{56}_{26}Fe$

30. Why are different conditions and reactions required to form nuclei after $^{56}_{26}Fe$?

Evolution of the Elements

Hydrogen is the most abundant element in the universe, followed closely by helium and then the other light elements. There is an unusually high abundance of elements near iron-56. (See Figure U2. Elements near iron-56 have the most stable nuclei.) Although 106 elements are known and the majority exist naturally on earth, scientists suspect that the elements represent a time sequence - from the lightest (hydrogen) building up to the heaviest elements.

There are many different kinds of stars visible in the sky. The sun is one of these and belongs to the group known as *main sequence stars*. (See Table U6.)

Table U6
Stellar Evolution

Type of Star	Relative Age	Characteristics
main sequence	young	-the heavier the star, the more light it emits
red giants	middle-aged	-very bright dense stars -glow with a red light
novas or supernovas	old	-enormous explosion that scatters material through space -probable fate of many stars

Evidence by astronomers and nuclear physicists points to the conclusion that the evolution of the elements is closely linked to the evolution of stars.

Energy Source of the Stars

Nuclear fission is not a possible source of energy in stars due to the very low abundance of fissionable isotopes in the universe. On the basis of the rates of reaction and the quantities of energy released, nuclear fusion appears to be the only candidate for the source of a star's energy. Nuclear fusion in a star appears to occur in an evolutionary sequence of processes.

1. Proton-Proton Process

In young stars (like the sun) there is an abundance of hydrogen which may be changed to helium through a series of reactions known as the proton-proton process.

$$4\,{}^{1}_{1}H \longrightarrow 2\,{}^{2}_{1}H + 2\,{}^{0}_{1}\beta + 2.8 \times 10^{8}\ kJ$$

$$2\,{}^{2}_{1}H + 2\,{}^{1}_{1}H \longrightarrow 2\,{}^{3}_{2}He + 1.1 \times 10^{9}\ kJ$$

$$2\,{}^{3}_{2}He \longrightarrow {}^{4}_{2}He + 2\,{}^{1}_{1}H + 1.2 \times 10^{9}\ kJ$$

Overall: $$4\,{}^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}\beta + 2.6 \times 10^{9}\ kJ$$

After all the hydrogen in the central core of the star is used up, the core cools and contracts. The contraction releases energy, increases the temperature and the star becomes a red giant with a hot helium core.

2. Alpha Process

When the helium core of the red giant reaches a temperature of 10^8 °C, helium nuclei fuse to a very unstable nucleus of beryllium-8. Most of the beryllium-8 breaks up immediately into helium nuclei, but occasionally a collision with another helium nucleus occurs before the beryllium-8 has a chance to break apart. This helium-beryllium reaction produces a stable carbon-12 nucleus. Other stable nuclei may now be produced by fusion with helium to form oxygen-16, neon-20 and magnesium-24. Further fusion reactions occur (with ${}^{4}_{2}He$ and ${}^{1}_{1}H$) producing heavier elements up to iron-56.

<u>Exercise:</u>

Complete the following equations to illustrate the alpha process.

1. $\_\_\_\_\_\_\_\_ \longrightarrow {}^{8}_{4}Be$
2. $\_\_\_\_\_\_\_\_ + \_\_\_\_\_\_\_\_ \longrightarrow {}^{12}_{6}C$
3. ${}^{12}_{6}C + {}^{4}_{2}He \longrightarrow \_\_\_\_\_\_\_\_$
4. $\_\_\_\_\_\_\_\_ + \_\_\_\_\_\_\_\_ \longrightarrow {}^{20}_{10}Ne$
5. ${}^{20}_{10}N + {}^{4}_{2}He \longrightarrow \_\_\_\_\_\_\_\_$

3. Processes in an Old Red Giant

After the depletion of helium and the formation of elements up to iron, the red giant collapses, temperatures rise and many of the remaining elements are formed by three processes. (See Table U7.)

Table U7
Nuclear Processes in an Old Red Giant Star

Type of Nuclear Process	General Characteristics	Examples
rapid (r)	-neutron absorption to produce many isotopes—particularly unstable isotopes -synthesizes heaviest isotopes of a given element	${}^{58}_{26}Fe + {}^{1}_{0}n \longrightarrow {}^{59}_{26}Fe$
slow (s)	-beta decay (neutron to proton conversion) of unstable isotopes formed by r-process	${}^{59}_{26}Fe \longrightarrow {}^{59}_{27}Co + {}^{0}_{1-}\beta$
proton (p)	-nuclei of existing heavy elements combine with protons to form the lightest isotopes of elements (not possible with the r-on s-processes)	${}^{59}_{26}Fe + {}^{1}_{1}p \longrightarrow {}^{60}_{27}Co$

The final stages of a red giant is often a tremendous explosion creating a nova or supernova and forming the heaviest elements. The remains of these explosions end up in other heavenly bodies - including the earth.

NUCLEAR CHEMISTRY
ENERGY CHANGES

Nuclear Binding Energy

A nucleus of helium-4 (an alpha particle) consists of two protons and two neutrons. In a one mole sample the sum of the masses of the individual nucleons is 4.031 883 g. However, the mass of one mole of helium-4 nuclei is 4.001 50 g. (See Table U2.) The difference in the masses is 0.030 38 g. This means that in the helium nucleus part of the mass is apparently missing.

According to Albert Einstein (1879-1955) mass and energy are equivalent. The amount of energy (E) equivalent to a mass (m) is calculated using $E = mc^2$ where c is the speed of light. The energy equivalent of the mass difference between the separate parts and a mole of helium-4 nuclei may be calculated as follows.

$$E = mc^2$$

$$= 3.038 \times 10^{-5}\ \text{kg} \times (3.00 \times 10^8\ \text{m/s})^2$$

$$= 2.73 \times 10^{12}\ \text{J} \qquad (1\ \text{kg} \bullet \text{m}^2/\text{s}^2 = 1\ \text{J})$$

$$\text{or} \quad 2.73 \times 10^9\ \text{kJ}$$

$$\text{or} \quad 2.73\ \text{TJ}$$

(equivalent to burning approximately 80 t of coal)

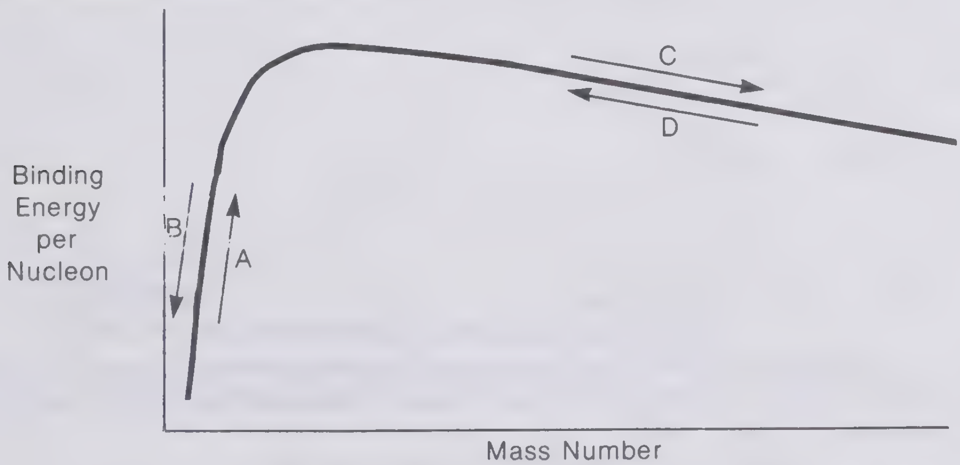
Two protons and two neutrons have 2.73×10^9 kJ more energy than a helium-4 nucleus. To understand this, recall that energy is released as particles bond together.

unbonded particles ⟶ **bonded particles** + **energy**

Binding energy is the energy released when nucleons combine to form a nucleus. The binding energy for a nucleus is calculated from the difference between the mass of the nucleus and the sum of the masses of its constituent nucleons.

Fission and Fusion

A nuclear reaction releases energy if it increases the binding energy per nucleon. A graph of the average binding energy per nucleon versus the mass number of nuclei (Figure U2) allows predictions to be made regarding energy changes in nuclear fission and fusion. On the graph below (Figure U10) the arrows indicate the direction of a nuclear reaction (reactant(s) ⟶ product(s)).



Binding Energy as a Function of Mass Number
Figure U10

Exercise:

Match the arrows on the above graph with the following nuclear reactions.

1. endothermic fusion ____________________
2. exothermic fusion ____________________
3. endothermic fission ____________________
4. exothermic fission ____________________

NUCLEAR CHEMISTRY
ENERGY CHANGES

Calculation of Energy Changes in Nuclear Reactions

The method of calculating binding energies can be used to calculate the energy changes associated with any nuclear reactions. If the change in mass, Δm, is calculated for any nuclear reaction, the Δm value represents the mass equivalent of the energy change. In this respect, the calculation of energy changes for nuclear reactions can be performed in a manner analogous to calculating heats of reaction for chemical reactions from heats of formation.

$$\Delta H = \Sigma H_f \text{ (products)} - \Sigma H_f \text{ (reactants)} \qquad \text{(chemical reaction)}$$

$$\Delta H = \Sigma m \text{ (products)} - \Sigma m \text{ (reactants)} \qquad \text{(nuclear reaction)}$$

The mass difference for nuclear reactions is the mass equivalent of the energy change. Using Einstein's relationship, $E = mc^2$, to convert the mass difference to an equivalent amount of energy, the energy change of a nuclear reaction becomes

$$\Delta H = \Delta mc^2 \qquad \text{where } \Delta m = \Sigma m \text{ (products)} - \Sigma m \text{ (reactants)}$$

In balancing nuclear equations ionic states are usually neglected. When calculating energy changes in nuclear reactions always use the mass of a neutral atom. In this way the mass of the electrons will "cancel out" and a correct answer will be obtained.

Example:

Calculate the ΔH for the following nuclear reaction.

$$^{2}_{1}H + {}^{1}_{0}n \longrightarrow {}^{3}_{1}H \qquad \mathbf{(m = nM)}$$

$$2.0140 \text{ g} + 1.008\,665\,0 \text{ g} \neq 3.016\,05 \text{ g}$$

$$3.022\,7 \text{ g} \neq 3.016\,05 \text{ g}$$

$$\begin{aligned}
\Delta m &= \Sigma m \text{ (products)} - \Sigma m \text{ (reactants)} \\
&= 3.016\,05 \text{ g} - 3.022\,7 \text{ g} \\
&= -0.006\,6 \text{ g} \\
&= -6.6 \times 10^{-6} \text{ kg} \\
\Delta H &= \Delta mc^2 \\
&= (-6.6 \times 10^{-6} \text{ kg})(3.00 \times 10^{8} \text{ m/s})^2 \\
&= -5.9 \times 10^{11} \text{ J} \\
&= -5.9 \times 10^{8} \text{ kJ}
\end{aligned}$$

Note:

$1 \text{ kg.m}^2/\text{s}^2 = 1 \text{ J}$

(equivalent to burning approximately 18 t of coal)

This particular reaction is exothermic. The mass of the system decreases and an equivalent amount of energy is released. Note that the nuclear binding energy per nucleon increased (see Figures U2 and U10) resulting in an exothermic reaction.

NUCLEAR CHEMISTRY
ENERGY CHANGES

Energy Changes Associated with Nuclear Reactions

The atomic molar masses of isotopes for the following problems are given on the ALCHEM data sheet.

1. Calculate $\triangle H$ for the following radioactive decay.

$$^{210}_{84}Po \longrightarrow \, ^{206}_{82}Pb + \, ^{4}_{2}He$$

2. Calculate $\triangle H$ for the following nuclear fusion.

$$^{2}_{1}H + \, ^{3}_{1}H \longrightarrow \, ^{4}_{2}He + \, ^{1}_{0}n$$

(Check the value obtained with that given for this reaction earlier in the notes.)

3. Calculate the binding energy of a $^{35}_{17}Cl$ nucleus. Note that the binding energy will be the $\triangle H$ value for the $^{35}_{17}Cl$ nucleus forming from its nucleons.

mass of one mole $^{35}_{17}Cl$ *nuclei* = 34.959 52 g

Energy Changes Associated with Nuclear Reactions

4. Calculate the energy required to break one mole of ${}^{14}_{7}N$ into its component nucleons. (Note: Allowance must be made for the orbital electrons since the ALCHEM data sheet lists the *atomic* molar masses.)

5. Calculate the energy associated with the following radioactive decay

$${}^{5}_{2}He \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

6. Calculate the energy required to break one mole of ${}^{56}_{26}Fe$ into its component nucleons. (See Note with Question 4.) Calculate and compare the binding energy per nucleon for ${}^{56}_{26}Fe$ and ${}^{14}_{7}N$. Which of the two nuclei are more stable?

NUCLEAR CHEMISTRY
ENERGY CHANGES

Table U8
Comparison of Energy Changes for Hydrogen

	Temperature (°C)	Process Occurring (Hydrogen Example)	Molecular Process	Approx. Magnitude of ΔH (kJ/mol)
	-273		almost no movement of molecules in perfect crystals	
	-259	*hydrogen melts* $H_2(s) \longrightarrow H_2(l)$	molecules vibrate around fixed points in the solid crystal	phase change 10^{-2} - 10^{0}
phase change	-253	*hydrogen boils* $H_2(l) \longrightarrow H_2(g)$	molecules move freely and rotate in the gaseous state	
	1.0×10^3			
surface of sun	1.0×10^4	*dissociation of hydrogen molecules* $H_2(g) \longrightarrow H(g) + H(g)$	vibrational energy exceeds chemical bond energy	chemical change 10^2 - 10^3
	1.0×10^5			
plasma	1.0×10^6	*ionization of hydrogen atoms* $H_{(g)} \longrightarrow H^+_{(g)} + e^-$	kinetic energy exceeds ionization energy	
center of stars	1.0×10^7	*fusion of hydrogen nuclei* $4\,^1_1H \longrightarrow \,^4_2He + 2\,^0_1\beta$	kinetic energy exceeds nuclear energy	nuclear change 10^7 - 10^{12}
supernova explosions	1.0×10^8	*proton process* $^1_1H + \,^{144}_{60}Nd \longrightarrow \,^{145}_{61}Pm$		

Exercise:

Rewrite equations for the sample hydrogen changes from Table U8. Include the approximate energy change as part of the equation.

1. melting:

2. boiling:

3. dissociating:

4. ionizing:

5. self-fusion:

6. fusion with $^{144}_{60}Nd$:

Table U9
Energy Changes and Their Applications

Phase Changes	Melting	main source of energy in weather
	Vaporization	industrial applications: - steam heating - refrigeration (steam heating and refrigeration: means of transmitting heat energy) - steam generators - means of changing chemical energy to mechanical or electrical energy
Chemical Changes	Combustion	- currently the world's main energy source (pollution is often a serious side effect)
	Biological	- living organisms use energy from chemical change
	Other	- electrochemical cells (including fuel cells) are used to generate electricity
Nuclear Changes	Fission	- technology still developing - currently used in nuclear reactors to generate electricity and to power submarines - atomic bomb
	Fusion	- technology still not developed - source of sun's energy - hydrogen bomb

NUCLEAR CHEMISTRY
ENERGY CHANGES

Phase changes, chemical changes and nuclear changes all involve changes in energy. The following equations represent reactions which can be used as commercial sources of energy.

1. Calculate the heat released when 1.00 kg of steam condenses.

$$H_2O_{(g)} \longrightarrow H_2O_{(l)} \qquad \Delta H = -40.7\ \text{kJ}$$

2. Calculate the heat released when 1.00 kg of hydrogen burns.

$$H_{2(g)} + \tfrac{1}{2}O_{2(g)} \longrightarrow H_2O_{(l)} \qquad \Delta H = -286\ \text{kJ}$$

3. Calculate the heat released when 1.00 kg of U-235 undergoes fission. (The atomic molar mass of ${}^{235}_{92}U$ is 235 g/mol.)

$$ {}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + 3\,{}^{1}_{0}n \qquad \Delta H = -1.90 \times 10^{10}\ \text{kJ}$$

4. Calculate the heat released when 1.00 kg of ${}^{1}_{1}H$ undergoes fusion to form ${}^{2}_{1}H$.

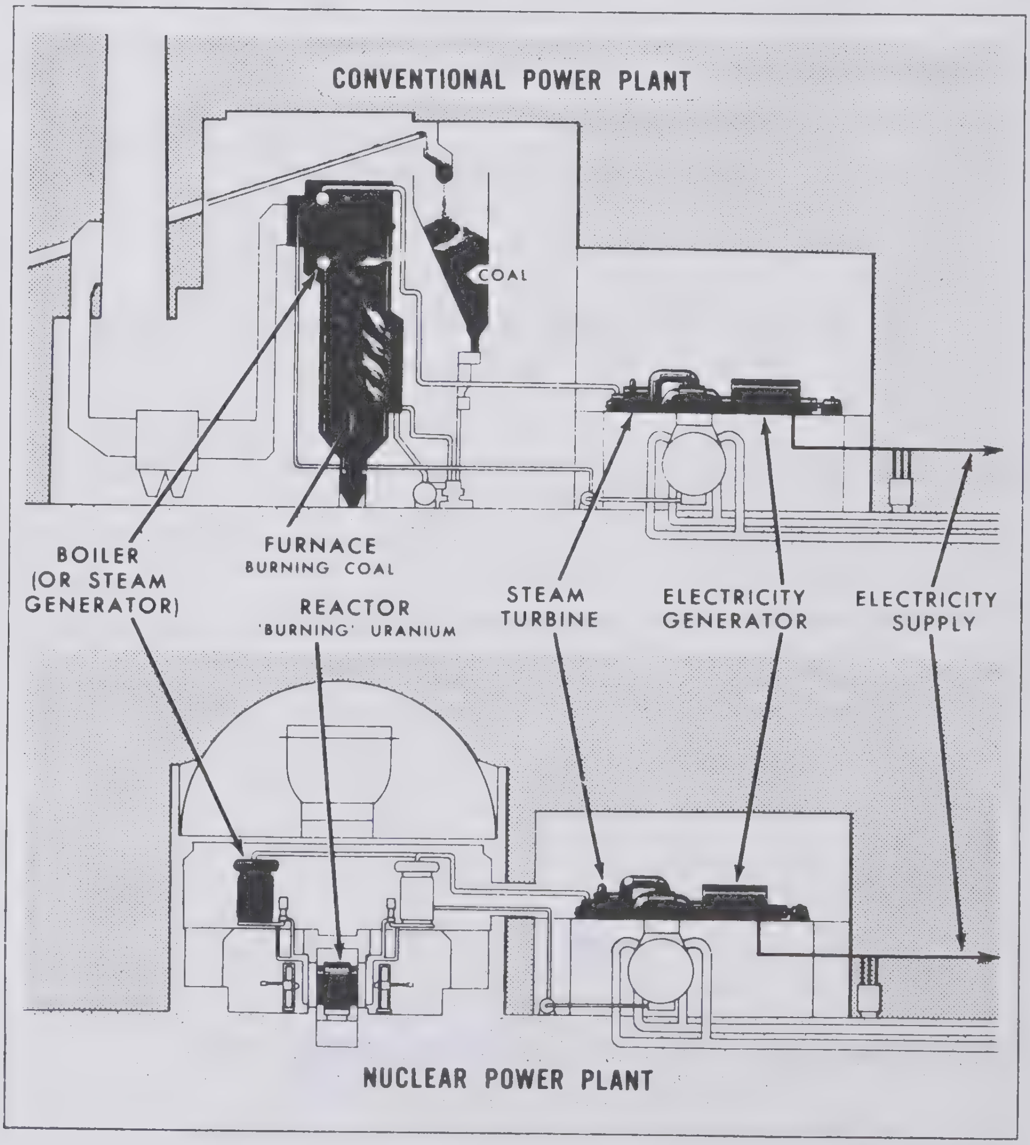
$$4\,{}^{1}_{1}H \longrightarrow 2\,{}^{2}_{1}H + 2\,{}^{0}_{1}\beta \qquad \Delta H = -2.8 \times 10^{8}\ \text{kJ}$$

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

Introduction

The demands for electrical power are ever increasing to the extent that per capita use of electricity has been doubling every 20 a. At one time, this meant simply dam a river and establish another hydroelectric site. However, most of the accessible hydroelectric sites have now been developed. Those remaining have high development costs and present environmental problems. Also, dams are in remote locations, so that the power would have to be transmitted over great distances. Consequently, the emphasis is now on thermal generation of electric power. Conventional thermal generation requires the fossil fuels - coal, oil or natural gas. However, the cost of both oil and natural gas has been sharply increasing in recent times. As well, oil and natural gas supplies are being depleted and there is uncertainty as to the availability of future supplies. There are also problems with coal. Western Canada has abundant coal supplies, but these are a long way from power stations in Central and Eastern Canada. Further, the sulfur content of coal presents pollution problems. The viable alternative to thermal generation using fossil fuels is thermal generation using nuclear power.

The basic principle of thermal generation is quite simple. Boil water and direct the steam into a turbine. The turbine turns the generator which produces electricity. In a conventional power plant, the best heat source is the combustion of fossil fuels. In nuclear power plants, the heat source is the nuclear fission process. The main difference lies in the source of heat used to make steam that drives the turbine. (See Figure U11.)



Difference Between Conventional Power Plant and Nuclear Power Plant
Figure U11

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

The Nuclear Process in Nuclear Power Plants

The nuclear fisson process presently used in nuclear power plants was first discovered by O. Hahn and F. Strassmann in Germany in 1939. This process involves bombardment of uranium with neutrons. When a neutron is absorbed by the nucleus of a uranium atom, the nucleus becomes unstable and splits (*fissions*) causing a relatively enormous release of energy. Spontaneous fission goes on in uranium all the time. But, travelling at up to 41 600 km/s, the escaping neutrons generally pass through other atoms without being absorbed by the nucleus. Thus they do not split enough atoms to start a chain reaction.

Neutrons, if they are to split uranium nuclei, must be slowed down or *thermalized* to about 1.0 km/s. The slow or *thermal* neutrons initiate fission reactions. The role of the *moderator* is to bring about the slowing down of neutrons without absorbing very many of the neutrons. The uranium neutrons ricochet against the moderator atoms, slowing down, then bouncing back into the uranium fuel and splitting atoms. Given enough fuel, this process sets up a chain reaction, providing steady heat. The heat turns water into steam that drives turbine generators to produce electricity.

To utilize natural uranium as a source of nuclear fission, one other problem has to be overcome. Not all uranium undergoes fission. Naturally occurring uranium consists of two main isotopes, U-238 and U-235. These two isotopes exist in widely differing proportions in natural uranium. U-235, the uranium isotope that undergoes fission, makes up only 0.7% of naturally occurring uranium. The remaining unfissionable U-238 makes up 99.3%. The utilization of uranium as a fuel for nuclear power plants is hampered by two obstacles - the small amount of U-235 present in natural uranium and the need for thermalizing the neutrons.

Enriched-Uranium Reactors

Physicists in U.S.A. solved the problems of low U-235 concentration and thermalizing neutrons in the following way. They constructed reactors that ran on enriched uranium (1.5 - 3% U-235) with ordinary or light water as a moderator. Ordinary water is very efficient at thermalizing the neutrons but it also absorbs some of the neutrons. The increased abundance of neutrons from the enriched uranium is balanced by the loss of some neutrons by absorption in the moderator.

CANDU Reactors

Canada has responded differently to the two problems. Canada's nuclear physicists came up with a system called CANDU-PHW or simply CANDU. CANDU-PHW stands for Canadian Deuterium Uranium - Pressurized Heavy Water. The Canadian system uses heavy water as both coolant and moderator. (Heavy water contains the isotope $^{2}_{1}H$, known as *deuterium*, instead of ordinary hydrogen.) The low neutron absorbing properties of the heavy water moderator allows the system to utilize uranium(IV) oxide (UO_2) derived from naturally occurring U_3O_8.

A Comparison of Reactors

Generally, the grade or quality of the fuel (percentage of U-235 in the fuel) determines the properties of the moderator required. A low grade fuel (uranium ore) requires a moderator with low neutron absorbing characteristics (i.e., heavy water) in order to minimize loss of neutrons. A high grade fuel (enriched uranium), which produces many more neutrons, allows for the absorption of more neutrons by the moderator (i.e., light water). Basically, the U.S.A. system enriches the fuel and the Canadian system enriches the moderator. The U.S.A. and Canadian systems represent two extremes in nuclear power plant design.

Exercise:
Define the following terms.

1. thermal neutrons —

2. moderator —

3. deuterium —

4. control rod —

5. heavy water —

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

6. What is the major purpose of a nuclear reactor?

7. Explain why thermal generation of energy using nuclear power is a viable alternative compared to that of using fossil fuels.

8. What factors would determine which parts of Canada might choose to develop nuclear power plants?

9. **What particles are used as initiators in nuclear reactors and what is the source of these particles?**

10. Why must a nuclear reactor be continually cooled?

11. **What two obstacles are encountered in using uranium oxide as a fuel for nuclear reactors?**

12. Compare how the U.S.A. and Canada responded to the problems considered in Question 11.

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

History of CANDU

Canada's nuclear power program has been developed over a period of three decades. The world's second reactor (the first outside the U.S.A.) was started up in Chalk River, Ontario in 1945. This reactor, called ZEEP for Zero Energy Experimental Pile, provided basic data on the use of natural uranium fuel and heavy water moderator. The ZEEP reactor was the forerunner for two other large research reactors located at Chalk River - the National Research Experimental (NRX) which began operating in 1947 and the National Research Universal (NRU) which was started up in 1957.

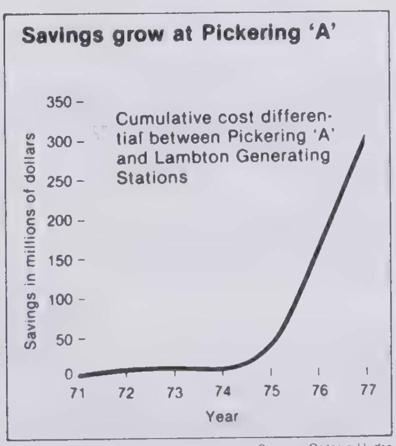
The research reactors operated by Atomic Energy of Canada Limited (AECL) led to the construction of nuclear power stations. Canada's first nuclear power station constructed at Rolphton, Ontario began to produce electricity in 1962. The 20 MW nuclear power station demonstrated the technical feasibility of using natural uranium, heavy water system for power generation. The Rolphton nuclear reactor was followed by the construction of another CANDU station at Douglas Point on Lake Huron. The Douglas Point 200 MW station produced its first electricity in 1967.

The next major development in Canada's nuclear power program was the construction for Ontario Hydro of one of the world's largest nuclear power stations at Pickering on Lake Ontario. This nuclear station consisting of four 500 MW units produced its first electricity in 1971. The Pickering 'A' plant established many records in the international field of nuclear power plant construction and operation. The success of Pickering has led to an accelerated pace of nuclear power plant construction in Ontario. As a result, a series of big nuclear power stations are being brought into service in Ontario. The first of these was the Bruce 'A' Generating Station on Lake Huron where four 750 MW units started up successively between 1975 and 1978. Douglas Point, Pickering 'A', and part of Bruce 'A' produced 28% of Ontario's electricity in 1977. Construction of Pickering 'B', consisting of four 600 MW units, and Bruce 'B' consisting of four 750 MW units, are scheduled for completion during the period 1981-1983. The next station to be completed is Darlington 'A' (four 850 MW units, similar to Bruce 'B') near Toronto. This will be followed by a new-design 1250 MW reactor with 732 (vs. 480) fuel channels which starts construction in 1980.

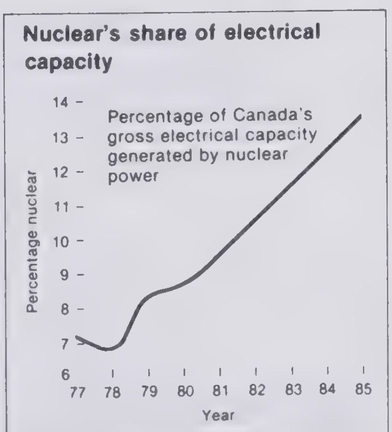
Hydro Quebec has one nuclear power station at Gentilly on the St. Lawrence River. The Gentilly prototype, producing 250 MW, is being used to explore the advantage of using boiling light-water as a coolant instead of heavy water. Gentilly-2, a second Quebec nuclear power plant (a CANDU-DHW) rated at 600 MW, came into operation in 1979. Gentilly-3 (size yet to be determined) is scheduled for the late 1980's.

Next to introduce nuclear power were the Atlantic provinces, with the first station (a 600 MW reactor) located at Point Lepreau, New Brunswick. Other provinces are likely to follow. How soon other provinces choose to develop nuclear power plants depends upon such factors as the regional demand for electricity and the availability and costs of energy resources. In 1977 Ontario Hydro did an economic comparison of generating costs between Pickering and Lampton (Ontario Hydro's best coal fired plant) and found that Pickering produced electricity at one-half the cost of Lampton.

Internationally, Canada has supplied nuclear power stations to India and Pakistan. In 1973 two other countries, Argentina and the Republic of Korea, chose the standard 600 MW Canadian reactors for their nuclear power stations. Other countries such as Italy, Japan and Romania have expressed interest in CANDU.



Source: Ontario Hydro



Source: Dept. of Energy, Mines and Resources

Heavy Water - Properties and Production

Hydrogen and oxygen combine to form water, H_2O. Similarly, heavy water is a combination of deuterium and oxygen to give D_2O. Deuterium differs from ordinary hydrogen in that it has a neutron in its nucleus. Thus ordinary water contains hydrogen-1 and heavy water contains hydrogen-2, called deuterium. The extra neutron makes the deuterium atom heavier than the hydrogen atom, hence the term heavy water for deuterium oxide.

Heavy water is a naturally occurring substance. It occurs in ordinary water in proportion approximately one molecule of heavy water to 7 thousand molecules of ordinary water. The mass of heavy water is about 10 percent more than ordinary water. Also, heavy water has a different freezing point (3.82 °C) and boiling point (101.42 °C) at standard pressure than ordinary water. Otherwise, both ordinary water and heavy water look and taste the same and their chemical and physical properties are so similar that the separation of the two is a difficult process.

All naturally occurring compounds of hydrogen also contain some deuterium. There are methods by which this deuterium can be extracted from hydrogen compounds. The process being used in Canadian plants involves the exchange of deuterium between water and hydrogen sulfide at different temperatures. This process is based on the fact that deuterium migrates to water at low temperatures and to hydrogen sulfide at high temperatures. In terms of equilibrium, this may be expressed by the following equation.

$$D_2O_{(l)} + H_2S_{(g)} \underset{\text{low temp.}}{\overset{\text{high temp.}}{\rightleftharpoons}} H_2O_{(l)} + D_2S_{(g)}$$

At high temperatures, equilibrium to the right is favoured, and at low temperatures equilibrium to the left is favoured.

The heavy water is produced by a suitable arrangement of flow of water and hydrogen sulfide in separating towers. In each tower the water flows down a series of perforated plates or traps, while hydrogen sulfide bubbles up through the trap. An exchange of deuterium between water and hydrogen sulfide occurs in a planned sequence. The manner is illustrated in Figure U11.

The hydrogen sulfide gas is progressively enriched in deuterium in several initial stages in an enriching unit. In a final stage, the deuterium enriched hydrogen sulfide gas gives up its deuterium to water. Deuterium enriched water (20-30 %) from the final stage passes to a finishing reactor where it is distilled to a nuclear reactor grade product that is 99.75 percent D_2O.

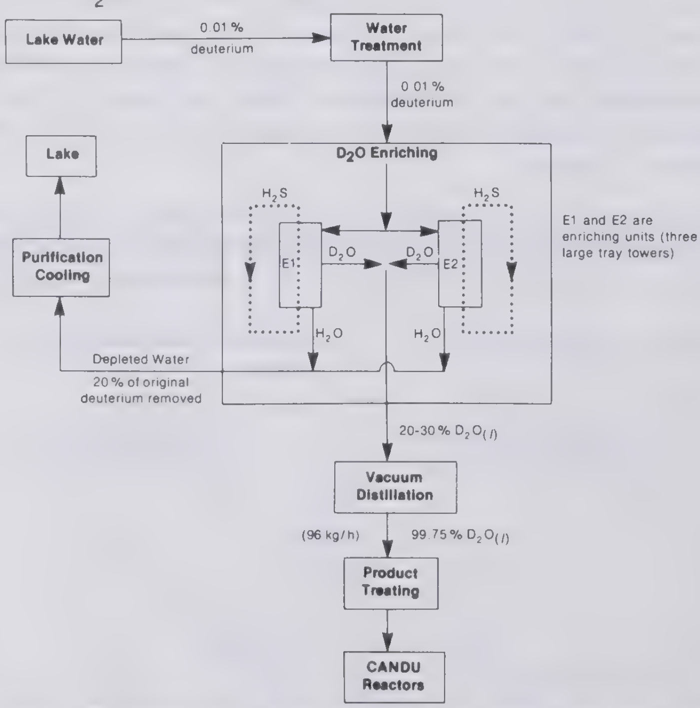


Figure U11

Major Processing Steps at Bruce Heavy Water Plant

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

Heavy Water in Reactor Systems

Heavy water has many of the advantages of ordinary water. It is stable, nontoxic and has a relatively high specific heat. Like ordinary water, heavy water is an excellent coolant material.

A good moderator should be relatively stable and a poor neutron absorber. Heavy water is by far the best moderating substance among those now in common use. Based on several factors, such as moderating properties, neutron absorption characteristics etc., heavy water is thirty times more efficient than ordinary water.

CANDU reactors require a heavy water inventory of approximately 0.8 Mg/MW of electrical power capacity. In addition small losses require the replacement of approximately 0.7 %/a (Pickering Station). At a cost of \$234/kg D_2O (1978), the heavy water accounts for approximately 12 % of the capital cost of a standard CANDU reactor.

Exercise:

1. Considering that the atomic molar mass of deuterium, ^2_1H, is 2.01 g/mol, verify that the heavy water, D_2O, has a molar mass about 10% greater than that of ordinary water.

2. The percent natural isotope abundance of heavy water in ordinary water is given in Table U3 as 0.015%. This converts to a percent by mass of 0.017% (i.e., 0.015 x 20.0 g/mol/18.0 g/mol). What mass and what volume of ordinary water would be required to produce 1.00L (1.10 kg) of D_2O by the method described earlier. (Assume 100% efficiency.)

3. *Optional.* Assumes knowledge of Le Chatelier's Principle.

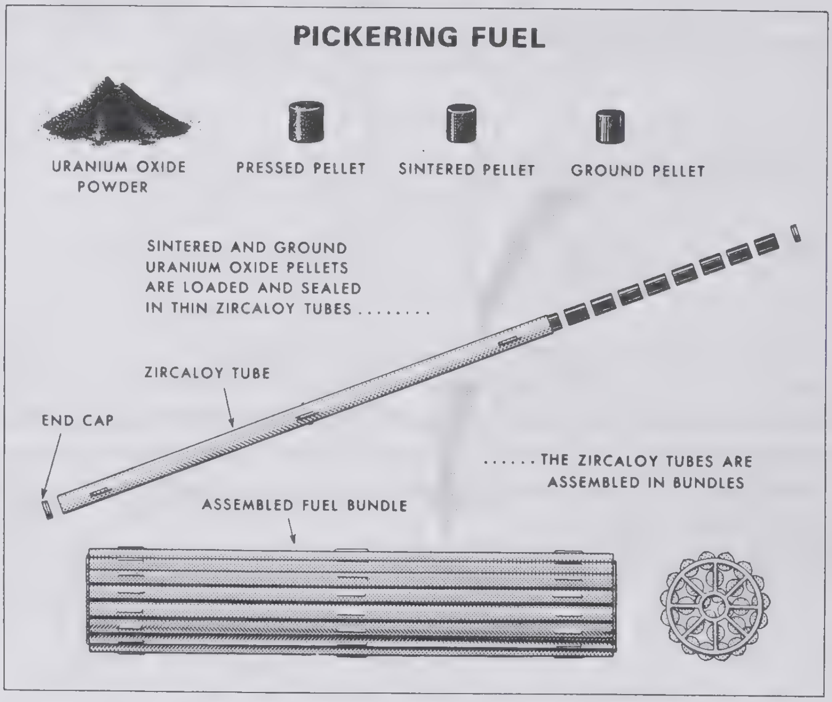
   Considering that the following equilibrium,

$$D_2O_{(l)} \quad + \quad H_2S_{(g)} \rightleftharpoons H_2O_{(l)} \quad + \quad D_2S_{(g)},$$

   is shifted to the right at high temperatures and to the left at low temperatures, is the reaction exothermic or endothermic? Explain using Le Chatelier's Principle.

Uranium Fuel for CANDU

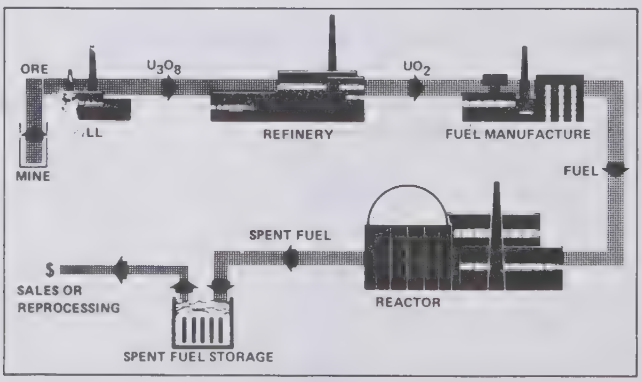
The uranium fuel for the CANDU reactor is processed by a nuclear fuel manufacturer into cylindrical uranium oxide fuel pellets. In this process uranium oxide is pressed into pellets, sintered and ground. In the sintering process, uranium oxide powder (in pellet form) is heated under pressure to produce a solid mass without going through a liquid state. This solid mass is better able to withstand the high temperatures and pressures encountered inside a nuclear reactor. The pellet is then ground to a precision shape and size. The processed pellets are placed inside thin (0.4 mm) Zircaloy tubes to form fuel rods (see Figure U13). Zircaloy is an alloy of zirconium and tin which retains its strength at high temperatures and has only a small tendency to absorb neutrons. The fuel rods are assembled to form single fuel bundles. The fuel bundles in turn are inserted into pressure tubes located in a large tank or calandria (see Figure U14). For example, each fuel bundle of 28 tubes in the Pickering 'A' Nuclear Generating Station is 495 mm long and contains 22.2 kg of uranium oxide. The fuel bundle is 92 % by mass UO_2 and 8 % by mass Zircaloy. Each reactor contains 4680 fuel bundles with a total mass of about 116 t. The heat produced by the 116 t of uranium oxide is equivalent to the heat provided by about three million tonnes of coal.



Uranium Fuel for the CANDU Reactor
Figure U13

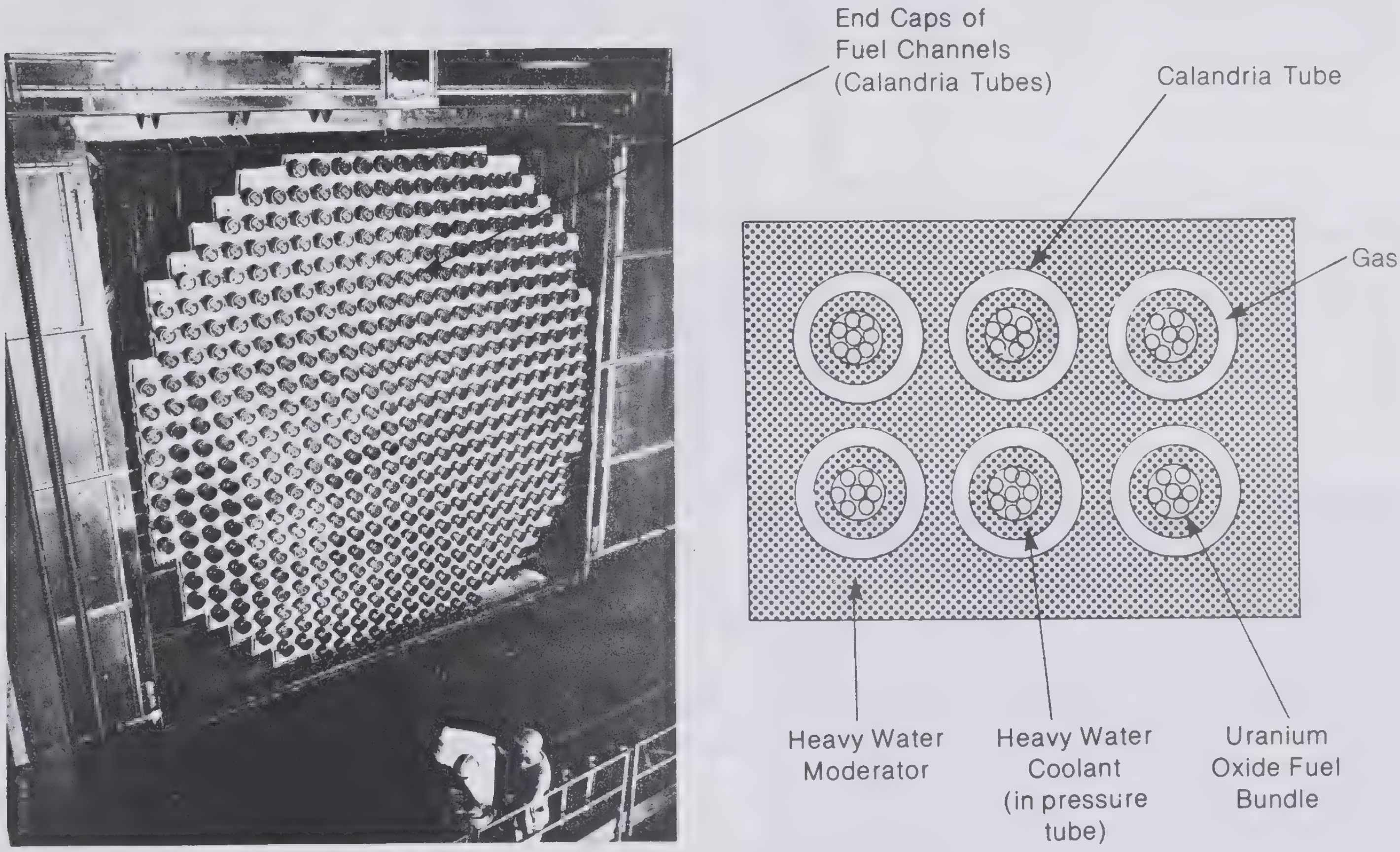
The 600 MW CANDU reactor, which has become the standard reactor size, has 380 fuel channels containing 12 bundles per channel. Each bundle contains 37 elements (tubes) with 29 pellets of UO_2 per element.

The full cycle of the fuel is illustrated below.



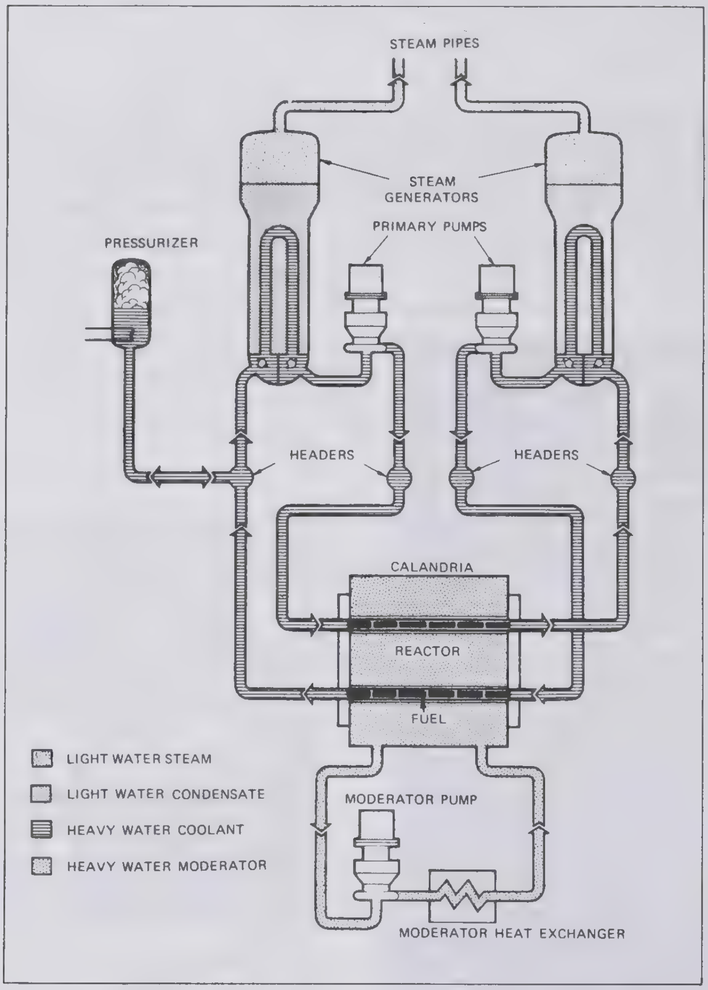
CANDU Reactor Core

The *calandria* is the heart of the nuclear power plant. In addition to containing the uranium oxide fuel bundles, the calandria contains heavy water that serves as a coolant, heat transfer medium and neutron moderator (see Figure U14). For example, the Pickering 'A' reactor contains 488 t of heavy water, both as a moderator and as a fluid in the heat transport system.



The Calandria of the Nuclear Reactor
Figure U14

As mentioned earlier, the calandria contains a large number of pressure tubes in which bundles containing uranium fuel are inserted. The heat produced by the fission of uranium atoms is transferred to the pressurized heavy water (PHW) coolant which is pumped through the pressure tubes. The pressure is maintained to prevent the heavy water from boiling. The heavy water leaves the reactor at a temperature of 293 °C and a pressure of 8825 kPa (87 atmospheres). After transferring heat to ordinary water in the steam generator, the heavy water is piped back to the reactor in a continuing cycle. This heavy water coolant fluid circulates in a closed system separate from both the heavy water moderator in the reactor and from the ordinary water in the steam generator system (see Figure U15). The space between the wall of the pressure tube and the calandria tube is filled with a gas which permits quick detection of leaks in the pressure tubes.



Schematic of the CANDU Nuclear Reactor
Figure U15

Reactor Operation

The calandria, around the pressure tubes, also contains heavy water used as a moderator to sustain the chain reaction in the fission of uranium fuel (see Figure U15). Two conditions must be met before the nuclear reactor *goes critical*, that is before a chain reaction is maintained. There must be sufficient moderator and there must be a sufficiently large quantity of uranium. For example, in the NRX (National Research Experimental) reactor at Chalk River, Ontario, about 15 t of heavy water and about 10 t of uranium oxide are required before the reactor goes critical.

To understand the aspect of a reactor going critical, consider the following general equation for the reaction that occurs in the uranium fuel.

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow \text{fission products (e.g., Ba, Sr, Rb, Cs)} + 2.4\,{}^{1}_{0}n + \text{energy}$$

The average 2.4 neutrons produced by the fission are fast. The objective in reactor design is to limit the loss of neutrons so that exactly one neutron survives to be absorbed by another nucleus of U-235 and thus maintain a steady chain reaction at its so called critical condition. The principle way of controlling the reaction during start up or shut down is by the use of shutoff rods containing strong neutron absorbers such as boron or cadmium. Emergency shutdown procedures involve the dropping of shutoff rods into the core, rapid injection into the moderator of a "liquid poison" (neutron absorber) such as a concentrated gadolinium nitrate solution, and/or rapid core cooling using light water. Duplicate and isolated emergency shutdown systems exist and in many cases the individual components are triplicated.

The normal control of the reactivity and power output of a CANDU reactor involves three separate systems. The primary method uses zone control absorbers. These are compartments, built into the reactor core, which are capable of being filled with light water (a neutron absorber). Additional systems use control and adjuster rods, similar to shutoff rods, but mechanically controlled.

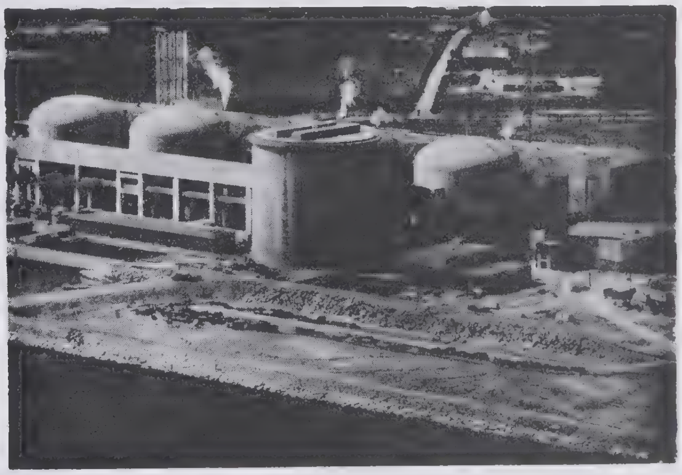
NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

Fuelling the CANDU Reactor

One of the features of CANDU reactors is on-power fuelling. Semi-automatic fuelling machines, controlled by computers, load new fuel and remove spent fuel. These machines automatically make pressure-tight connections, remove sealing and shielding plugs, insert and remove the fuel and then reclose the pressurized fuel channels. As a new fuel bundle is pushed into one end of a tube, the spent fuel bundle is removed from the other end. Bundles are inserted and removed from various parts of the calandria in a planned sequence to ensure efficient burnup. The efficiency of burnup gives CANDU the lowest fuelling cost of any reactor system. The spent fuel bundles are mechanically transferred to the station's spent fuel storage bay. Here the spent fuel is stored under more than 6 m of water until sale or disposal. The precautions in storing fuel bundles is exemplified by the Pickering storage bay. The bay is lined with steel-reinforced 35 cm thick concrete walls and a 30 cm concrete floor. The spent fuel is then stored under 8 m of water. The bay provides enough space to hold spent fuel for approximately forty-two years.

Generation of Electrical Power

The final component of the nuclear power plant is the power generating portion which is the same regardless of the kind of reactor supplying heat (see Figure U16). In this portion, steam passes through the turbine blades and imparts energy in the form of rotary motion to the turbine shaft. The rotation of the turbine shaft turns a generator which produces electricity. The *spent* steam after leaving the turbine, enters the condenser and is converted to water. The water (condensed steam) is pumped back to the nuclear steam supply system where the cycle starts all over again with the conversion of the water to high pressure and high temperature steam. The most common method of cooling is by pumping cool water through the condensing tubes and back to the source which is a river, lake or some other large body of water.

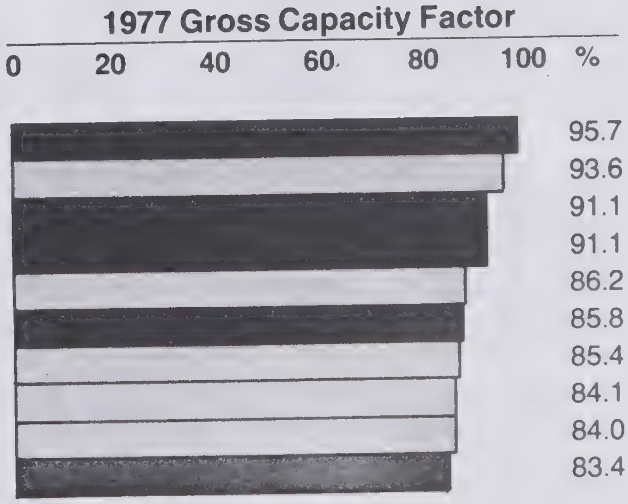


Includes all units > 500 MW gross in-service as of January 1, 1977

- Boiling Water Reactor
- Pressurized Water Reactor
- Pressurized Heavy Water Reactor
- Gas Cooled Reactor

1977 Performance

	Country	Unit	Rating (MW)	Years In Service	1977 Gross Capacity Factor (%)
1.	Canada	Pickering 3	540	6	95.7
2.	W Germany	Stade 1	662	6	93.6
3.	Canada	Pickering 4	540	4	91.1
4.	Canada	Pickering 2	540	6	91.1
5.	USA	Prairie Island 2	547	3	86.2
6.	Canada	Pickering 1	540	6	85.8
7.	USA	Palisades	722	6	85.4
8.	USA	Point Beach 1	524	7	84.1
9.	Japan	Genkai 1	559	3	84.0
10.	USA	Millstone 1	690	7	83.4



Differences Between CANDU and Other Reactors

All present-day nuclear reactors operate on the same basic principle - the fission of uranium-235 to liberate energy. Heat energy released by fission is transferred to steam which drives an electric generator. The principal differences between reactors involve the choice of fuel, moderator and coolant.

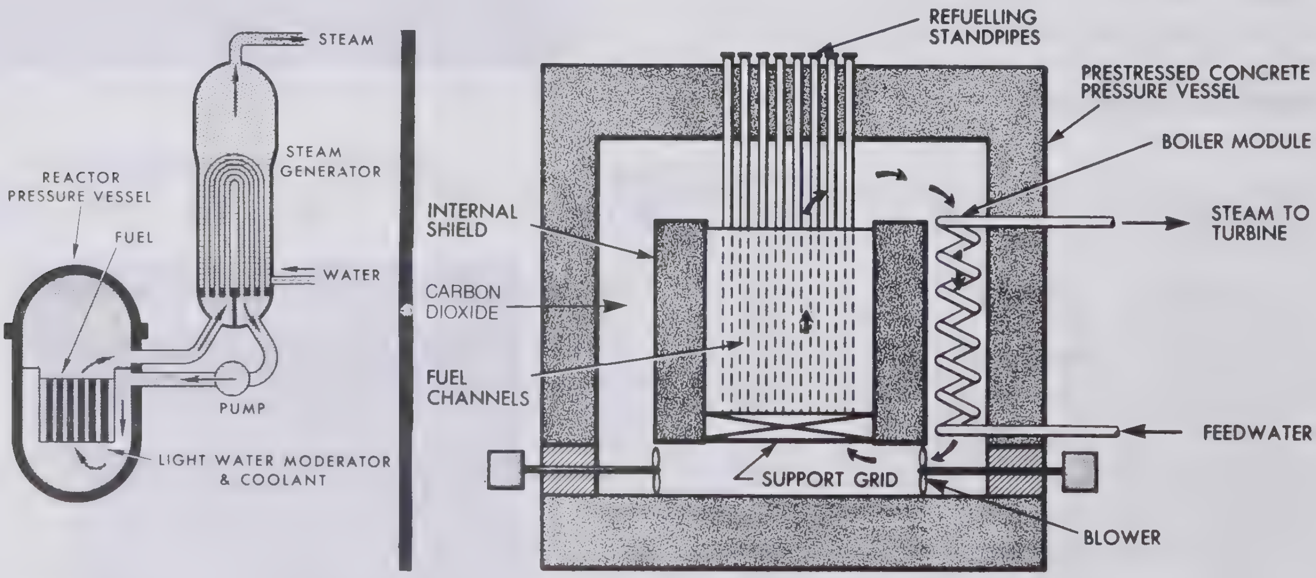
The CANDU reactor uses natural uranium fuel and the efficient moderator, heavy water, to cause a controlled chain reaction. Other countries use less efficient moderators and as a result must use enriched uranium.

Table U10 compares CANDU with its principal rival on the world market, the U.S. light water reactor (LWR) and a third reactor type the advanced gas cooled reactor (AGR) developed in Great Britain.

Table U10
Comparison of CANDU with Other Reactors

Reactor	Fuel	Moderator	Coolant
CANDU	natural uranium	heavy water	heavy water
LWR	enriched uranium	ordinary water	ordinary water
AGR	enriched uranium	graphite	carbon dioxide

Another important difference between CANDU and the U.S. light water reactor exists in the fuel, moderator and coolant arrangement. As Figure U17 shows, the LWR uses a large steel vessel containing the combined light water coolant and moderator under pressure. The fuel rods are suspended in the vessel and can only be removed by shutting the reactor down (ordinarily once a year). CANDU uses pressure tubes to separate the moderator from the coolant. The CANDU moderator is not pressurized, while the coolant is circulated under pressure in individual fuel channels.



LWR and AGR Reactors
Figure U17

Advantages of the CANDU System

1. Natural Uranium Fuel

Natural uranium, which is plentiful in Canada is relatively simple and inexpensive to process compared to the processing of enriched uranium. The use of a very efficient moderator, heavy water, ensures a much more efficient use of uranium by deriving twice as much power per unit mass compared to other reactors.

Spent fuel reprocessing plants are not necessary to allow an economic operation. The unfissioned U-235 (0.2 %) and the fissionable product, Pu-239 (0.3 %) will provide dividends in the future when the technology of reprocessing improves. (Spent fuel rods can also be sold for their plutonium content.)

2. Reactor Design

The individual, pressurized fuel bundles result in several advantages. On-power fuelling eliminates expensive shut-down periods and also enables leaking or faulty fuel bundles to be replaced before any major problem occurs. Another advantage of the pressure tube design is that it allows flexibility in the design of the reactor fuels (thorium cycle) or coolants (organic liquid).

3. Safety

The CANDU has several important safety advantages over its competitors. First, because the pressure tubes of CANDU reactors are much easier to inspect for cracks and corrosion during operation than the steel or concrete vessels, this *essentially* eliminates the risk of catastrophic pressure vessel failure. Second, an accidental loss of coolant would likely be less severe and easier to control in CANDU than in LWR. Third, CANDU's larger size and lower power density makes it much easier to control. Finally, problems of waste control and disposal are much simpler than with the enriched uranium reactions. (There are some who still question the safety of even the CANDU reactor. Not for reasons of nuclear explosions, but for reasons of steam explosions due to *melt downs* and resulting in radioactive contamination.) (Melt downs result from loss of coolant flow.)

Disadvantages of the CANDU System

1. Cost

The major disadvantage of the CANDU system, at least in the short term, is the high capital cost involved. This is offset by lower fuel costs over the long term (compared to conventional and other nuclear systems). The cost and availability of the uranium fuel (at least for some countries) may change the economics over a long period of time.

A significant factor in the high capital cost and in operating costs is due to the heavy water. The estimated cost of D_2O for one Pickering unit is about 25 million dollars. Heavy water is expensive to produce and new cheaper methods of production are not foreseen.

2. Safety - Heavy Water

The use of heavy water in reactors also results in the production of radioactive tritium oxide ($^{3}_{1}H_2O$). (Tritium is an isotope of hydrogen, $^{3}_{1}H$.) Tritium oxide (also loosely called *tritium*) emits beta negative (β^-) particles and has a half-life of 12.3 a. Tritium oxide can enter the body by inhalation, ingestion and by skin absorption. The internal radiation then damages cells within the body. Irradiated heavy water containing tritium oxide (about seven parts per million) may evaporate when exposed to the air or may be spilled during refuelling and reprocessing. Although no serious accidents have occurred, a few leaks have occurred and a potential problem is present.

3. Safety - Spent Fuel

The spent fuel is more dangerous than the feed fuel for three reasons. First, the spent fuel is more radioactive than the feed fuel. The feed fuel may even be handled by hand, but 6-8 m of water cover is used to protect workers from radiation from the spent fuel. The storage and ultimate disposal of radioactive nuclear wastes are very serious problems. Currently wastes are being stored for possible economic advantages (see breeder reactors) and no disposal of wastes has been made. Current thinking is that wastes, immobilized in glass or ceramic, may be disposed down holes drilled deep in the earthquake free Canadian shield.

Second, the plutonium-239 produced from the uranium-238 in the CANDU reactor may used by purchasing countries as fuel for an atomic bomb. India, for example, has already built and exploded an atomic bomb from plutonium-239 obtained from the spent fuel of a purchased CANDU reactor. Canada now seeks guarantees from purchasing countries that they will not use the spent fuel for the purpose of building bombs.

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

1. Suggest a possible reason why uranium metal is not used as fuel in nuclear reactors.

2. Draw and label a small cross-section of the calandria. Explain the statement, ''the calandria is the heart of the CANDU nuclear reactor''.

3. State two functions of heavy water in the CANDU nuclear reactor.

4. What two conditions must be met in the CANDU system before the nuclear reactor goes critical?

5. The following general equation expresses the energy reaction that uranium fuel undergoes.

$$^{235}_{92}U + \underset{\text{(slow)}}{^{1}_{0}n} \longrightarrow \text{fission products} + 2.4\,^{1}_{0}n + \text{energy}$$

In terms of the general equation, explain what must be done to maintain the reactor at its critical condition.

6. What is the principal way of controlling reaction rate in the CANDU reactor during start up or shut down?

7. What *fail safe* procedures, in addition to the principal method mentioned in Question 6, are used to control the reaction rate in the CANDU reactor?

NUCLEAR CHEMISTRY
NUCLEAR REACTORS AND THE CANDU SYSTEM

8. U-238 upon capturing a neutron undergoes a sequence of reactions which can be partially represented as follows.

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U$$

$$^{239}_{92}U \longrightarrow ^{239}_{93}Np + ^{0}_{-1}\beta \qquad t_{1/2} = 23 \text{ min}$$

$$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta \qquad t_{1/2} = 2.3 \text{ d}$$

The plutonium-239 is fissionable and also radioactive (alpha decay, $t_{1/2}$ = 24.4 ka). Which isotopes would be present to the greatest extent in uranium spent fuel? Explain.

9. Why must spent nuclear reactor fuel be stored in concrete, water-filled bays?

10. Explain the chief differences between the Canadian CANDU nuclear reactor and the United States LWR nuclear reactor.

11. What main feature of the design of the CANDU nuclear reactor gives it advantages over other reactors?

12. The use of heavy water moderator gives the CANDU system what important disadvantages?

13. What are the favorable and the unfavorable expectations regarding the use of stored spent fuel from CANDU nuclear reactors?

Atomic Energy of Canada Limited

The Atomic Energy of Canada Limited (AECL) is a Canadian government federal crown corporation which employs over 6000 personnel in six major groups.

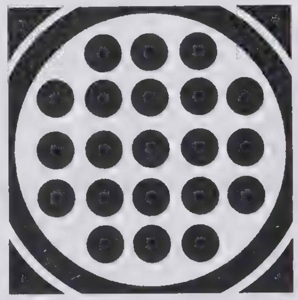
1. AECL Head Office
2. Chalk River Nuclear Laboratories (CRNL)
3. Power Projects
4. Whiteshell Nuclear Research Establishment (WNRE)
5. Commercial Products
6. Heavy Water Projects

The short descriptors of each group illustrates the diversity of the AECL nuclear program. Although the nuclear reactor gains the most recognition from the electricity it produces, there are many other direct and indirect applications of the reactor program. Some of these other applications are described on the pages which follow.

AECL's objective is the utilization of atomic energy for peaceful purposes. To this end it promotes, assists and performs atomic energy research and development that will meet near and long-term Canadian needs for low cost energy and will be commercially attractive to other countries. It also endeavours to widen and improve the practical application of atomic energy in industry, agriculture and medicine.

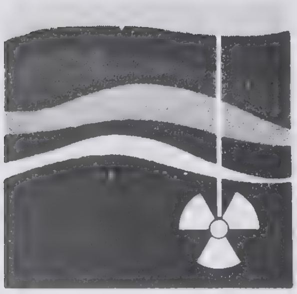
The Company's major research and development centres are the Chalk River Nuclear Laboratories in Ontario, and the Whiteshell Nuclear Research Establishment in Manitoba. The responsibilities of the research centres are to:

- *Pursue basic research activities in biology, physics, and chemistry.*
- *Provide a complete range of facilities for applied research and engineering development projects in support of the nuclear program.*



AECL's nuclear power engineering group, Power Projects, is located in the Sheridan Park Research Community, near Toronto. Power Projects' other facilities are located at Meadowvale, Ontario and Montreal, Quebec. The group is responsible for:

- *Engineering and development of the CANDU nuclear power system.*
- *Management of nuclear power station projects.*

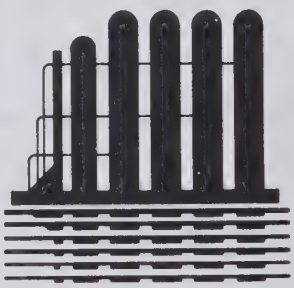


The Company's waste management program is directed by the Whiteshell Nuclear Research Establishment, Pinawa, Manitoba. The responsibilities of this group are to:

- *Research, develop and demonstrate methods of permanent disposal of radioactive wastes.*
- *To ensure that such disposal is done in a safe and environmentally acceptable manner.*

Commercial Products (CP) designs and manufactures radiation equipment and markets radioisotopes and related services. CP comprises three separate groups:

- *Medical Group — cancer treatment equipment.*
- *Industrial Group — irradiation equipment for sterilization of medical supplies.*
- *Isotope Group — radioisotopes for industrial, medical, and research applications.*



The Company's Heavy Water Projects with headquarters in Ottawa, operates two production plants in Nova Scotia; one at Glace Bay and the other at Port Hawkesbury. A third plant, La Prade, is being built near the Gentilly nuclear complex in Quebec.

Applications of Nuclear Reactors

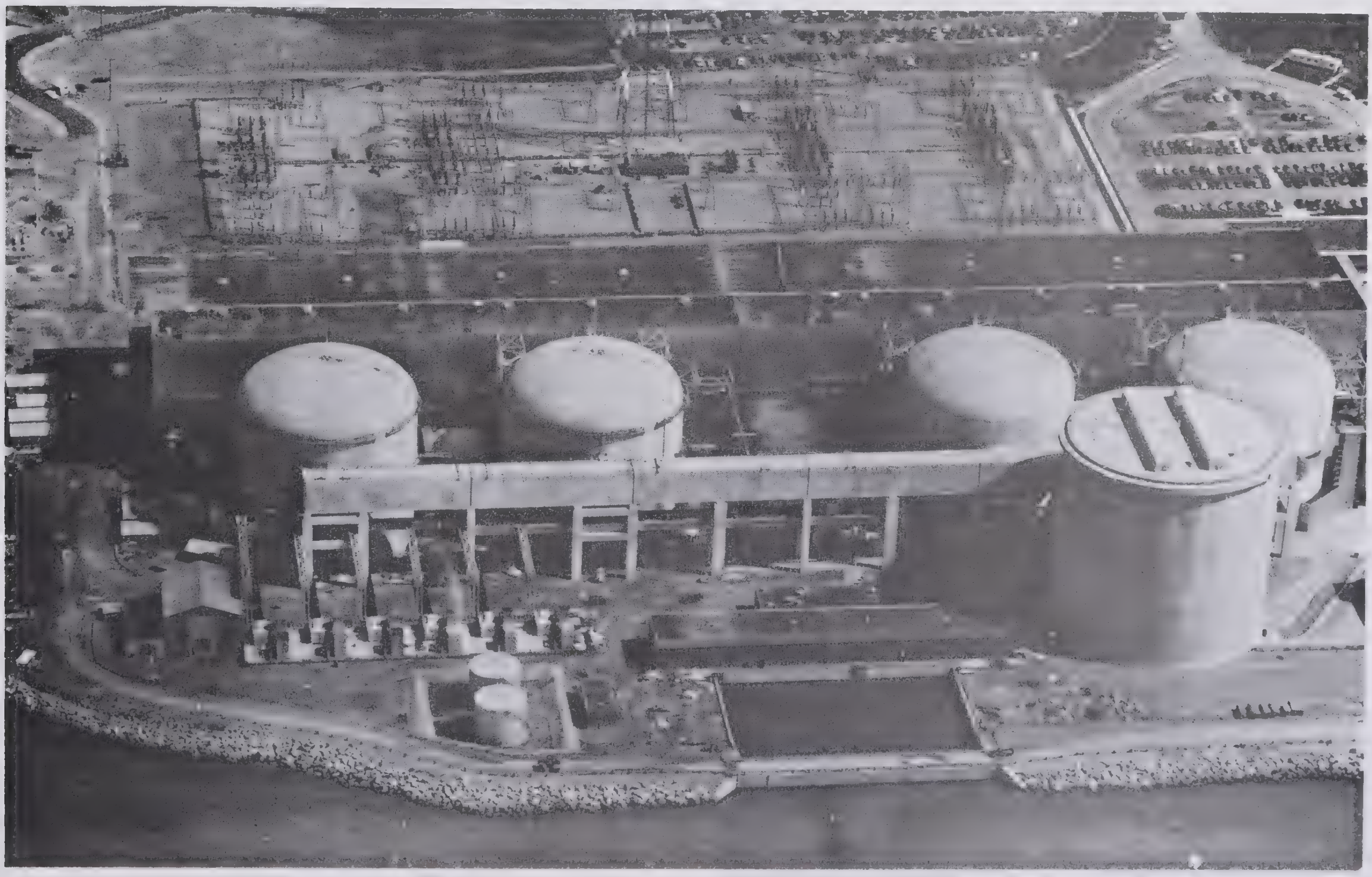
The applications of nuclear reactors described in this section are:

1. electric power generation
2. research
3. producing radioisotopes for industry
4. producing radioisotopes for agriculture
5. producing radioisotopes for medicine
6. production of nuclear fuels

Although the major application of nuclear reactors is the production of electrical power, the other applications are important to our current and future lifestyle. Special reactors may be used for research, production of radioisotopes and/or production of nuclear fuels or a regular power generating nuclear reactor may be used for some of these purposes. For example some CANDU's are fitted for the production of radioisotopes such as cobalt-60.

1. Nuclear Reactors for Electric Power Generation

The use of nuclear reactors for the production of electric power was described in the previous section. The worlds most efficiency nuclear power station - Pickering 'A' - is pictured below on the shore of Lake Ontario. The four cylindrical round-topped buildings house each of the four 540 MW CANDU reactors. The large cylindrical flat-topped building is a vacuum building. The vacuum is used for emergency shutdown. The turbines and generators are housed in the long building immediately behind the four reactors. The four Pickering 'B' reactors are immediately to the right of the photo of Pickering 'A'.



Pickering 'A' Nuclear Power Station

NUCLEAR CHEMISTRY
APPLICATIONS OF NUCLEAR REACTORS

In addition to the use of nuclear reactors for the production of heat energy from fission, nuclear reactors have other important applications. Reactors can be used as instruments for research. They can be used to produce radioisotopes, such as Co-60, Ir-192, Na-24, Cs-137, Sr-90, Ca-45, S-35, C-14 and Kr-85, which are used in industry, agriculture and medicine. The cobalt-60 is produced in a Pickering 'A' reactor while the approximately thirty other radioisotopes are produced at Chalk River. Reactors can also be used to produce new nuclear fuels from nonfissionable elements.

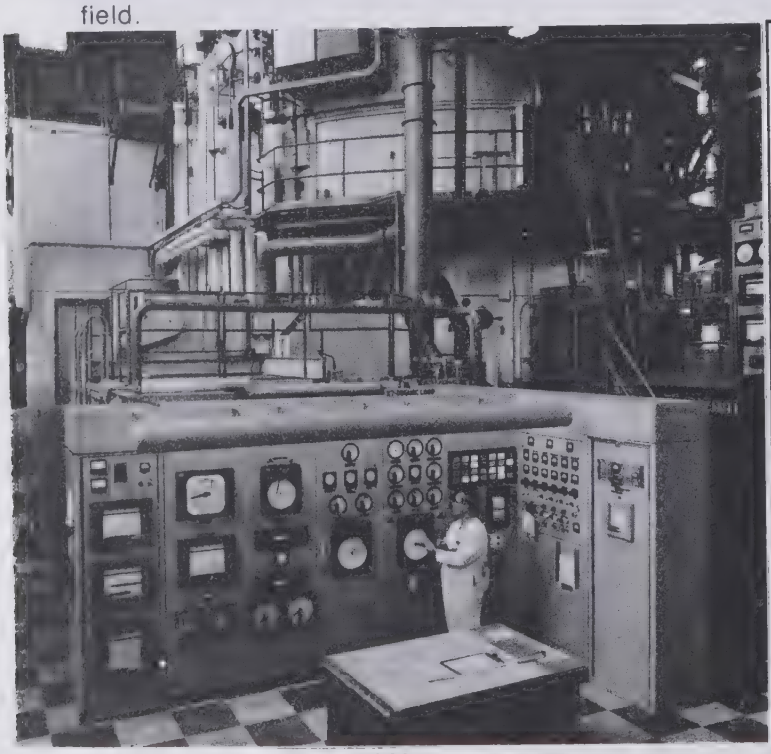
2. Use of Nuclear Reactors in Research

Much basic and applied research is conducted by Atomic Energy of Canada Limited (AECL). This includes research in nuclear physics, nuclear chemistry, radiobiology, reactor physics, reactor fuels, radiation chemistry, materials science, environmental radioactivity and the physics of solids and liquids.

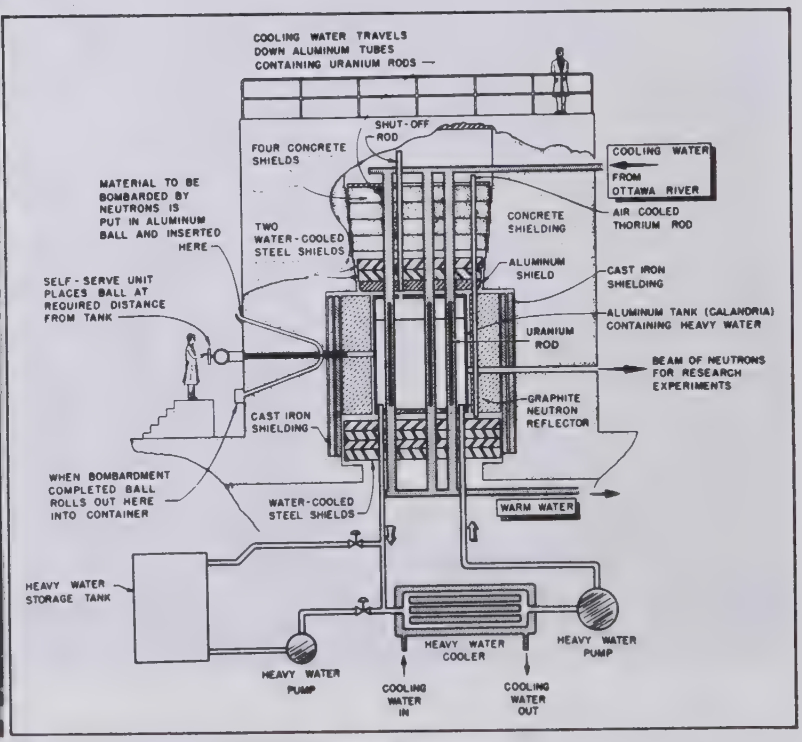
Various Canadian nuclear reactors are involved in research. Construction of the largest Canadian nuclear research establishment - Chalk River Nuclear Laboratories (CRNL) - was started in 1944. CRNL spearheaded the Canadian programme to find and develop peaceful uses of atomic energy. Two of the largest CRNL reactors - the National Research Experimental (NRX) which began operation in 1947, and the National Research Universal (NRU), which was started up in 1957 - are useful in many ways. NRX and NRU are constructed so that materials placed near reactor cores can be subjected to high neutron bombardment to produce artificial radioisotopes for medical research, cancer therapy and industrial uses. These reactors also have complex systems known as *loops* for testing fuels, coolants and other material for nuclear power stations.

Another unique experimental facility maintained by AECL is the WR-1 reactor at the Whiteshell Nuclear Research Establishment (WNRE) in Manitoba. WR-1 is the world's only operating heavy water moderated reactor cooled by an organic (oil) fluid and has given Canada a leading position in organic coolant technology. This reactor is designed to be used for a variety of engineering tests with differing fuels and fuel channels as well as a variety of reactor coolants. In addition, WR-1 is studying the effects of radiation on plants in order to improve quality and disease resistance. Work in chemistry includes studying the reaction mechanisms of chemical change and providing analytical services from a world recognized laboratory.

Of significance, is Canada's education and training of personnel in nuclear energy in conjunction with its nuclear program. As a result, Canada is not only providing the knowledge and skills for its own diversification in nuclear technology, but also making available trained personnel to other countries that enter the nuclear power field.



The NRX Reactor at Chalk River



NRX Flow Diagram

3. Industrial Applications of Radioisotopes from Nuclear Reactors

A complete description of all the industrial processes utilizing radioisotopes is too extensive to be undertaken here. Only some of the processes are mentioned below. The radioisotopes used are produced in a nuclear reactor.

1. The radioisotope, cobalt-60, which emits β^- and γ radiation is used as a substitute for high-powered x-ray machines for detecting defects in thick metal castings. In this regard, iridium-192, which emits gamma radiation of about a third the power of cobalt-60, is extensively used for the examination of welds in pipelines and vessels.

2. Radioisotopes have been used to study the effectiveness of lubricants. This has involved the use of radioactive metal isotopes as components of metal parts. The amount of wear in the metal can be determined from the quantity of radioactive isotope that shows up in the lubricant.

3. Radioisotopes are used for gauging the thickness of manufactured materials such as plastics, metal foils and sheets. The amount of radiation passing through the material can be related to its thickness.

4. Radiation from highly radioactive isotopes improves the polymerization process of butyl rubber, polyethylene and other hydrocarbons.

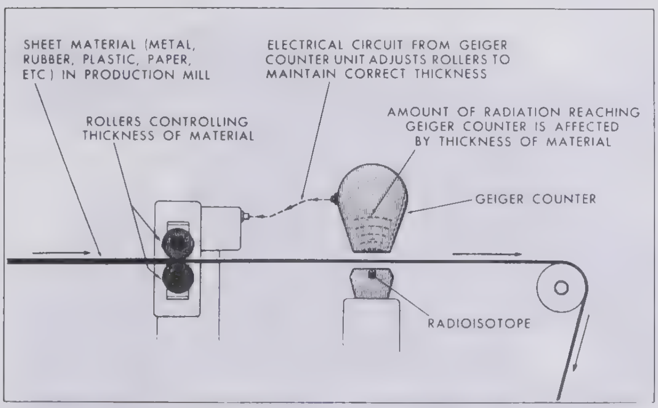
5. Many radioactive isotopes can be used for tracing chemical reactions to determine mechanisms of reaction (i.e., the exact way a reaction occurs) and structural configurations (i.e., detailed shapes) of the compounds involved.

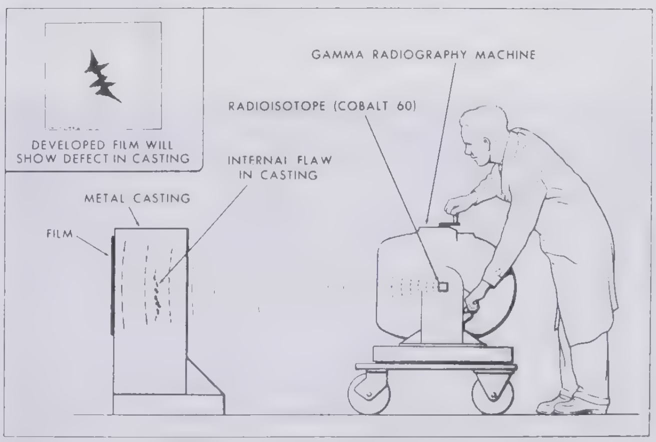
6. Radioisotopes are used for determining the surface area of particles in slurries and powders.

7. Radioisotopes are extensively used with phosphors to produce luminous dials on watches, gauges and switches. The radiation given off by radioisotopes causes the phosphors to glow.

8. Radiation from radioisotopes is used to sterilize antibiotics and medical supplies.

9. The use of radioisotopes as tracers finds wide application in metallurgical processes, in oil drilling holes, for testing pipelines and for tracing pollutants in air, soil and water.





Radioactive Isotopes are Used for Radiography and Thickness Gauging.

4. Agricultural Applications of Radioisotopes from Nuclear Reactors

Unstable (radioactive) atoms behave chemically like their stable counterparts until after they emit their radiation. Because their chemistry is the same, radioisotopes play an important role as tracers in various aspects of agriculture. Some of the many applications of radioactive tracers to agriculture are mentioned in the following list.

1. Radioactive isotope tracers give information as to what happens to fertilizers in the soil. For example, using radioactive phosphorus-32 scientists found that as much as 50 to 70 percent of the phosphorus in a plant came from the fertilizer during the first two to three weeks of growth. As well, radioisotopes have given answers to such questions as, do plants absorb fertilizers through roots only, where should fertilizers be placed and do root uptake processes have powers of discriminating between elements.

2. Radioactive tracers make it possible to measure chemical uptake of disease spores and to follow chemical fungicides through the plant. As well, radioactive tracers make it possible to predict the value of various chemicals as herbicides.

3. Radioactive tracers permit measurement of how nutritious various feedstuffs are and how efficiently these feedstuffs are assimilated.

4. Radioactive isotopes have been used to study insects, their life cycles, their efficiency as pollen carriers and for identifying parasites and predators.

5. Insects harmful to crops may be controlled by using radiation to sterilize male insects which are then released into a breeding area. A second generation of insects is much smaller in number as a result of this type of program.

6. Radiation from radioactive isotopes has been used to produce mutations that have been beneficial. Some examples include grains with stronger stems, new types of flowers and new strains with disease resisting capabilities.

7. Radioisotopes can be used for preserving foods. The principle of preserving foods by radiation is based on the fact that if, under proper conditions, gamma radiation from a radiation source is allowed to pass through food, the rays will kill or reduce the number of microorganisms in the food. The method for preserving foods employs low power radiation at a level that causes ionization. Such ionizing radiation intended for the irradiation of food does not make the food radioactive.

Radiation Inhibition of Sprouting in Onions

Treating a root with radioactive solution to examine motion of sap in a tree.

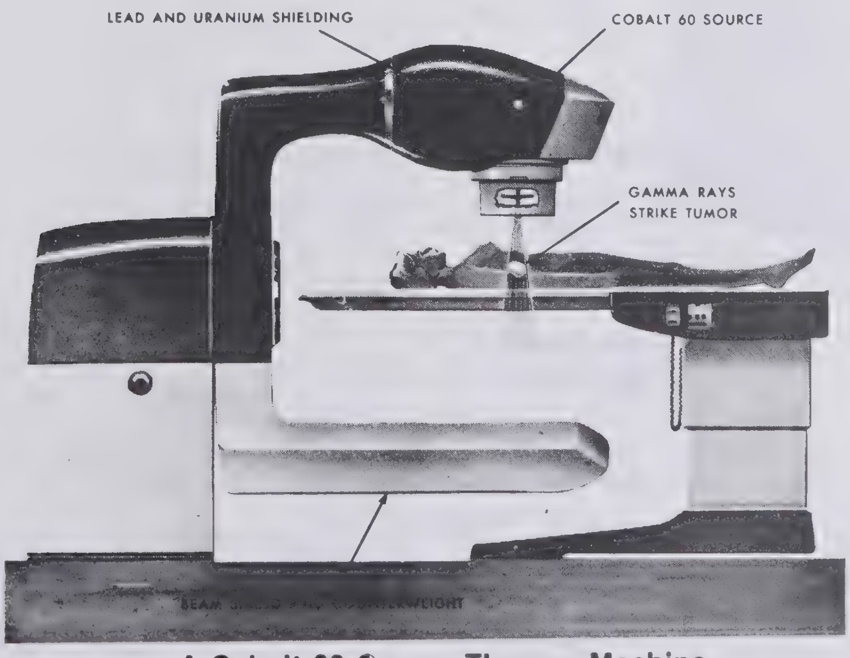
5. Medical Applications of Radioisotopes from Nuclear Reactors

Radioisotopes in medicine may be used in two different ways. Radiation emitted by the radioisotope may be used to trace the path of a chemical or the location of an abnormality within the body. In general, tracers are used for *analysis* and *diagnosis*. Radiation from a radioisotope may also be used to irradiate specific cells or organs in the *treatment* or *therapy* of a medical problem.

1. The use of radioisotope tracers in diagnosis may be illustrated by the following example. Suppose a patient is being diagnosed for a suspected tumor in the liver. Radioisotope radiation measurement can be used to aid the physician in his diagnosis. First, trace quantities of a radioactive isotope that would concentrate in the liver would be administered by intravenous injections. The radioisotope tracer could be administered with a carrier which could transport the isotope to the liver. In this case, a colloid of sulfur could be used as the carrier for the radioactive tracer, technetium-99, which is a gamma emitter. After the sulfur carrier and technetium tracer are injected into the veins, they will be ingested by the liver cells. A gamma ray scanner or camera would then produce an image of the gamma emission distribution that would indicate whether a tumor was present in the liver. The affected area has a different absorption rate.

   The procedure described in the previous paragraph is representative of the use radioisotopes for medical diagnosis. Specific radioisotopes that are concentrated by particular organs and cells are available. These isotopes can be used to differentiate between normal and malignant tissues, to measure such things as liquid volumes, rate of flow or rate of transfer through organs and membranes or to show the behaviour of internal organs.

2. *Radiation therapy* involves the use of concentrated sources of radiation that are localized to the desired cells or organs. The dosage is maintained so as to give maximum theraputic effect without harming adjacent healthy tissues. The concentrated source of radiation may be administered in one of two ways. A source of radiation is enclosed in a radiation tight container, from which a narrow collimated beam of concentrated radiation can be directed on the localized area. This is done in the case of treatment with cobalt-60. The other method involves intravenous injection, for example, iodine-132 for irradiation of thyroid cells. In this method, isotopes with short half-lifes are used. Therefore, after the localized area is irradiated, the isotope loses its activity rapidly enough to present little hazard by the time it is released to the blood stream. For example, iodine-132 with a half-life of 2.33 h would be preferred for treatment of a thyroid condition to iodine-131 with a half-life of 8.1 d. The use of radiation therapy destroys the cells subjected to the concentrated radiation. However, diseased or malignant cells are particularly vulnerable to radiation because of their self-reproducing nature. Particular isotopes, concentrated by a specific organ, are used in radiation therapy by intravenous injection in the same way as diagnostic use of radioisotopes. Radioisotope therapy through intravenous injection is much less frequently used than external irradiation (i.e., less than one percent of all cases involving radiation therapy).

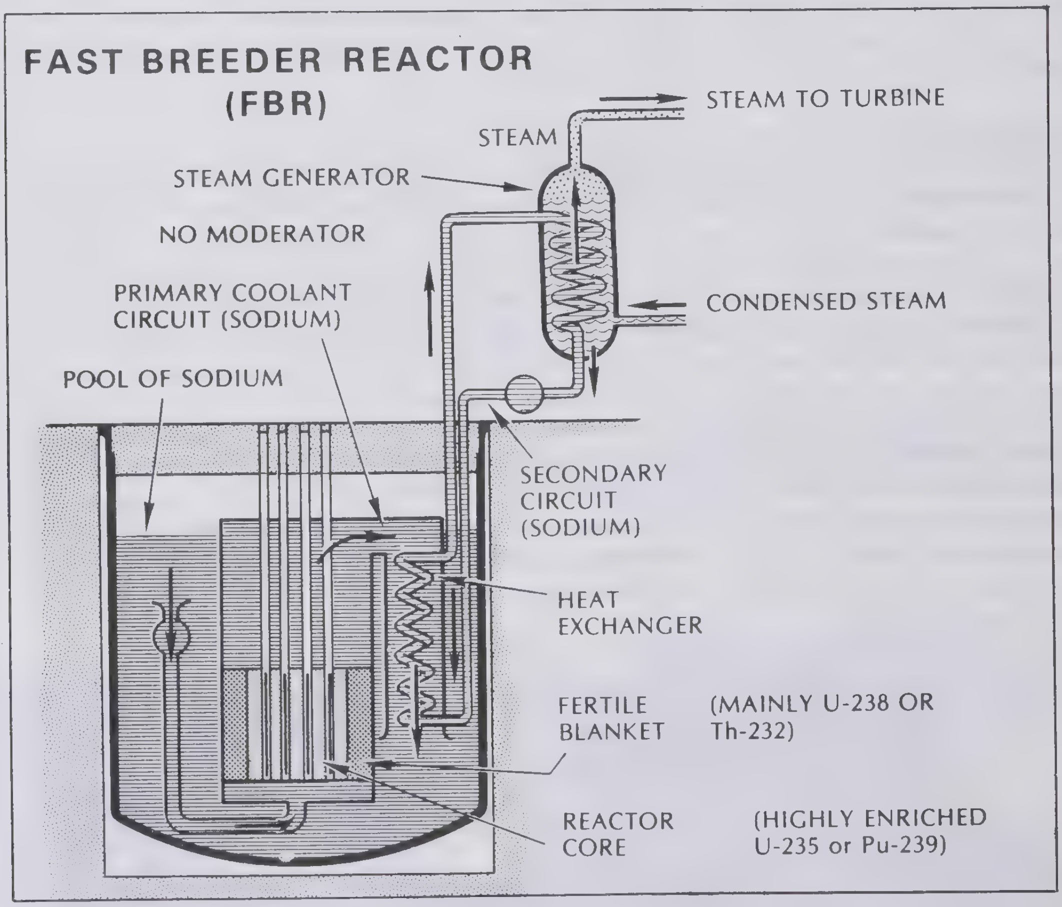


A Cobalt-60 Cancer Therapy Machine

Treatment with AECL cobalt therapy machines has increased the life expectancy of 6.5 million people in 75 countries.

6. Application of Nuclear Reactors to the Production of Nuclear Fuels

Scientists have learned that nuclear reactors can make fissile nuclear fuel from nonfissionable (fertile) atoms. Such a reactor, known as a *breeder reactor*, not only releases energy through fission but may produce more fissionable atoms than it consumes. This can happen because on the average 2.4 neutrons are released at each fission of a uranium-235 nucleus. Suppose 100 fissions occur and 240 neutrons are released. To maintain the chain reaction, 100 of these neutrons would be required, leaving 140 surplus neutrons. Some of the 140 surplus neutrons will be lost by escaping and by being captured by fission products and construction materials of the reactor. Suppose that the reactor design is such that 110 of the 140 surplus neutrons remain to be captured by uranium-238. This would result in the production of 110 atoms of fissionable plutonium. Therefore, 100 U-235 atoms underwent fission and 110 Pu-239 atoms were produced. This gives a 10% increase over fuel consumed. Similarily, thorium-232, when placed in a reactor, would be transformed into a fissionable uranium-233. Since both plutonium-239 and uranium-233 have half-lives in the thousands of years, they may be stored for future use as nuclear fuel for reactors. Although, several small breeder reactors have been constructed, these reactors are very complex and expensive to build, maintain and operate. Eventually, however, their technology may be refined so that they can be used to breed fissionable fuel economically and safely.



Breeder Reactor
Figure U18

NUCLEAR CHEMISTRY
APPLICATIONS OF NUCLEAR REACTORS

1. State four functions that can be attributed to nuclear reactors.

2. Give at least two contributions made by the nuclear reactors involved in research.

3. The most common isotope of cobalt is nonradioactive cobalt-59. Write an equation for the production of cobalt-60 (for cancer therapy) from cobalt-59 which has been inserted into a Pickering 'A' nuclear reactor. What stellar process is similar?

4. Cobalt-60 is used in detecting defects in metal castings and in medical radioisotope therapy. Knowing that cobalt-60 emits β^- and γ radiation, write the equation for this step of its radioactive decay with a half-life of 5.27 a.

5. Naturally occurring iridium is 37 % $^{191}_{77}Ir$. Iridium-192 is used by radiographers for photographing pipe and vessel welds. Write an equation for the production of $^{192}_{77}Ir$ in a Chalk River reactor, and another equation for the radioactive decay (β^- and γ) with a half-life of 74 d.

6. List at least five applications of radioisotopes in industry.

7. List four uses of radioisotope tracers in agriculture.

NUCLEAR CHEMISTRY
APPLICATIONS OF NUCLEAR REACTORS

8. Normal blood is about 1 % sodium chloride (ordinary salt). This fact makes possible the use of sodium-24 in some measurements of the blood and other fluids. When ordinary salt is exposed to high neutron bombardment in a nuclear reactor, the sodium-23 captures a neutron and becomes sodium-24, which in turn emits gamma radiation as it decays to magnesium-24. Write equations of the transformations of sodium-23 to sodium-24, and then the sodium-24 to magnesium-24. Why is the gamma radiation important?

9. Compare the use of radioisotopes for diagnostic and for therapeutic purposes.

10. Why would radioisotopes with short half-lives be used for the internal administration of radioisotopes for therapy?

11. Technetium-99, because of its short half-life of six hours, is coming into use for diagnosis of brain tumors using scanning devices. Technetium-99 lasts such a short time it cannot be kept in stock so it is prepared from the radioactive decay of molybdenum-99. Neutron capture by a stable isotope of molybdenum is used to prepare the radioactive Mo-99 ($t_{1/2} = 66$ h). Write equations for the production of Mo-99 and Tc-99.

12. Write equations for the production of the two possible reactor fuels from nonfissile starting material in a breeder reactor.

13. Explain how a breeder reactor can produce more fissionable material than it consumes.

NUCLEAR CHEMISTRY
OVERVIEW

Overview

The following series of questions provide an overview of the content of this nuclear chemistry unit.

Complete Table U11.

Table U11
Structure of Isotopes

	Name	Isotope Notation	Atomic Number	Mass Number	Subatomic Particles			Net Charge on Species
					Protons	Neutrons	Electrons	
1.	cobalt	$^{58}_{27}Co$						
2.	cobalt			60				
3.	iodide ion			127				
4.	iodide ion					78		
5.		$^{234}_{90}Th$						
6.	plutonium					145		
7.				32	15			0
8.						13	10	1+

How do the atomic number and mass number of resulting nuclei differ from the original nuclei after:

9. an α particle is emitted

10. a β^- particle is emitted

11. a β^+ particle is emitted

12. an γ ray is emitted

13. List three factors that affect nuclear stability.

NUCLEAR CHEMISTRY
OVERVIEW

14. What one thing is evident from a plot of numbers of protons as a function of number of neutrons in stable nuclei?

15. Which one of the nuclei, $^{235}_{92}U$ or $^{238}_{92}U$, is likely to be more stable? Propose a possible explanation.

What type of radioactive emission is a nucleus likely to undergo if its instability is due to:

16. too high a n/p ratio

17. too low a n/p ratio

Write a nuclear equation for each of the following processes.

18. positron decay of $^{22}_{11}Na$

19. β^- decay of $^{214}_{83}Bi$

20. alpha decay of $^{226}_{88}Ra$

The fission of uranium gives a variety of fission products. Complete the following equation by giving the isotope notation of the missing product.

21. $^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{139}_{54}Xe + \underline{\hspace{6em}} + 2^{1}_{0}n$

22. $^{235}_{92}U + ^{1}_{0}n \longrightarrow \underline{\hspace{6em}} + ^{94}_{36}Kr + 3^{1}_{0}n$

23. $^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{103}_{42}Mo + \underline{\hspace{6em}} + 2^{1}_{0}n$

24. $^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{135}_{53}I + ^{97}_{39}Y + \underline{\hspace{6em}}$

25. Some isotopes for medical or research purposes that have a short half-life need to be produced regionally because of losses during transit. What mass of $^{24}_{11}Na$ from a 20.0 g sample would be left after 60 h?

NUCLEAR CHEMISTRY
OVERVIEW

26. A piece of charcoal from an excavation is found to have a carbon-14 to carbon-12 ratio that is 12.5 % that of the atmosphere. How old is the speciment?

In the next three questions, compare the nuclear reactions of nuclear fission and nuclear fusion with respect to:

27. what happens to the nuclei undergoing fission and fusion.

28. the kind of nuclei that are likely to undergo fission and fusion reactions.

29. the change in binding energy per nucleon from the reactant(s) to the products.

30. Calculate the binding energy of a ${}^{12}_{6}C$ nucleus.

31. Calculate ΔH for the following nuclear reaction.

$${}^{15}_{7}N + {}^{1}_{1}H \longrightarrow {}^{12}_{6}C + {}^{4}_{2}He$$

32. What is the principle involved in the manufacture of heavy water? Relate this principle to the equilibrium process.

NUCLEAR CHEMISTRY
OVERVIEW

In the next two questions, describe the CANDU nuclear reactor system with respect to:

33. the kind of fuel and method of fueling.

34. the arrangement of fuel bundles, coolant and moderator. (Draw a sketch.)

35. The unique nature of the CANDU nuclear reactor permits the use of natural uranium oxide as a fuel. Explain.

36. Write equations for the production of $^{4}_{2}He$, $^{16}_{8}O$, $^{114}_{49}In$, $^{121}_{50}Sn$ and $^{123}_{51}Sb$ in stellar reactions by p-p, alpha, p, r and s processes respectively.

37. The rate of production of carbon-14 from nitrogen-14 by cosmic ray neutrons matches the rate of decay of carbon-14 into nitrogen-14, so that the percentage of total carbon-14 in the atmosphere and living material is constant. Write the equations for the continual production of carbon-14 and its subsequent spontaneous radioactive decay. How is the measurement of the carbon-14 to carbon-12 ratio used for carbon dating?

38. Uranium-238, the most abundant isotope of natural uranium, will not undergo fission. However, in breeder reactors as well as in other nuclear reactors, uranium-238 is converted into plutonium-239, which is capable of fission. In this conversion, uranium-238 changes to uranium-239, the uranium-239 changes to neptunium-239, which finally changes to plutonium-239. Write the equations for the three-step conversion of uranium-238 to plutonium-239. Note that in this process a fissionable energy source has been produced from a relatively abundant nonfissionable material. In CANDU reactors, approximately one-half of the energy obtained is the result of Pu-239 fission. Write an equation for a possible fission of plutonium-239.

...ry

data sheet

Canada metric

6. Two Place Logs

No.	Log	No.	Log	No.	Log	No.	Log	No.	Log
1.0	.00	3.0	.48	5.0	.70	7.0	.85	9.0	.95
1.1	.04	3.1	.49	5.1	.71	7.1	.85	9.1	.96
1.2	.08	3.2	.51	5.2	.72	7.2	.86	9.2	.96
1.3	.11	3.3	.52	5.3	.72	7.3	.86	9.3	.97
1.4	.15	3.4	.53	5.4	.73	7.4	.87	9.4	.97
1.5	.18	3.5	.54	5.5	.74	7.5	.88	9.5	.98
1.6	.20	3.6	.56	5.6	.75	7.6	.88	9.6	.98
1.7	.23	3.7	.57	5.7	.76	7.7	.89	9.7	.99
1.8	.26	3.8	.58	5.8	.76	7.8	.89	9.8	.99
1.9	.28	3.9	.59	5.9	.77	7.9	.90	9.9	1.00
2.0	.30	4.0	.60	6.0	.78	8.0	.90	1.00	.00
2.1	.32	4.1	.61	6.1	.79	8.1	.91	1.01	.00
2.2	.34	4.2	.62	6.2	.79	8.2	.91	1.02	.01
2.3	.36	4.3	.63	6.3	.80	8.3	.92	1.03	.01
2.4	.38	4.4	.64	6.4	.81	8.4	.92	1.04	.02
2.5	.40	4.5	.65	6.5	.81	8.5	.93	1.05	.02
2.6	.41	4.6	.66	6.6	.82	8.6	.93	1.06	.03
2.7	.43	4.7	.67	6.7	.83	8.7	.94	1.07	.03
2.8	.45	4.8	.68	6.8	.83	8.8	.94	1.08	.03
2.9	.46	4.9	.69	6.9	.84	8.9	.95	1.09	.04

7. Solubilities

t = 25°C P = 101 kPa

$HCl_{(aq)}$	*38%	12.4 mol/L
$H_3PO_{4(aq)}$	85%	14.7 mol/L
$HNO_{3(aq)}$	69%	15.4 mol/L
$CH_3COOH_{(aq)}$	99.5%	17.4 mol/L
$H_2SO_{4(aq)}$	94%	17.6 mol/L
$NH_{3(aq)}$	28%	14.8 mol/L
$NaOH_{(aq)}$	50%	19.1 mol/L
$AgCl_{(aq)}$		4.1×10^{-6} mol/L
$CaCO_{3(aq)}$		6.9×10^{-5} mol/L
$Ca(OH)_{2(aq)}$		6.9×10^{-3} mol/L
$C_{12}H_{22}O_{11(aq)}$		3.8 mol/L
$NaCl_{(aq)}$		5.3 mol/L

* percent by mass

8. Acid-Base Indicators at 25°C

Indicator	pH Range	$HIn_{(aq)}$	$In^-_{(aq)}$
methyl orange	3.1—4.4	red	yellow
methyl red	4.2—6.3	red	yellow
litmus	6.5—7.5	red	blue
bromthymol blue	6.0—7.6	yellow	blue
phenolphthalein	8.0—9.6	colorless	red
alizarin yellow	10.1—12.0	colorless	violet

9. Relative Strengths of Acids and Bases

	Name of Acid Species	Percent Reaction of 0.10 mol/L Solution	Reaction of 0.10 mol/L Aqueous Acid Species with $H_2O_{(\ell)}$	Name of Base Species	
1 Strong Acids	perchloric acid	100	$HClO_{4(aq)} + H_2O_{(\ell)} \xrightarrow{6} H_3O^+_{(aq)} + ClO^-_{4(aq)}$	perchlorate ion	
	hydroiodic acid	100	$HI_{(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + I^-_{(aq)}$	iodide ion	
	hydrobromic acid	100	$HBr_{(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + Br^-_{(aq)}$	bromide ion	2
	hydrochloric acid	100	$HCl_{(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + Cl^-_{(aq)}$	chloride ion	
	nitric acid	100	$HNO_{3(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + NO^-_{3(aq)}$	nitrate ion	
	sulfuric acid	100	$H_2SO_{4(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + HSO^-_{4(aq)}$	hydrogen sulfate ion	
3	hydronium ion	100	$H_3O^+_{(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)} + H_2O_{(\ell)}$	water	Decreasing Strength of Bases
Decreasing Strength of Acids	oxalic acid	53	$HOOCCOOH_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + HOOCCOO^-_{(aq)}$	hydrogen oxalate ion	
	sulfurous acid ($SO_{2(aq)} + H_2O_{(\ell)}$)	32	$H_2SO_{3(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + HSO^-_{3(aq)}$	hydrogen sulfite ion	
	hydrogen sulfate ion	29	$HSO^-_{4(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + SO^{2-}_{4(aq)}$	sulfate ion	
	methyl orange[7]	—	$HMo_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + Mo^-_{(aq)}$	methyl orange ion	
	phosphoric acid	24	$H_3PO_{4(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + H_2PO^-_{4(aq)}$	dihydrogen phosphate ion	
	hydrofluoric acid	8.2	$HF_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + F^-_{(aq)}$	fluoride ion	
	nitrous acid	7.3	$HNO_{2(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + NO^-_{2(aq)}$	nitrite ion	5
	bromthymol blue[7]	—	$HBb_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + Bb^-_{(aq)}$	bromthymol blue ion	
	benzoic acid	2.6	$C_6H_5COOH_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + C_6H_5COO^-_{(aq)}$	benzoate ion	
	hydrogen oxalate ion	2.3	$HOOCCOO^-_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + OOCCOO^{2-}_{(aq)}$	oxalate ion	
	ethanoic (acetic) acid	1.3	$CH_3COOH_{(aq)} + H_2O_{(\ell)} \rightleftharpoons H_3O^+_{(aq)} + CH_3COO^-_{(aq)}$	acetate ion	
	carbonic acid ($CO_{2(aq)} + H_2O_{(\ell)}$)	0.21	$H_2CO_{3(aq)} + H_2O_{(\ell)} \xleftarrow{6} H_3O^+_{(aq)} + HCO^-_{3(aq)}$	hydrogen carbonate ion	
	phenolphthalein[7]	—	$HPh_{(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + Ph^-_{(aq)}$	phenolphthalein ion	
	hydrogen sulfide	9.8×10^{-2}	$H_2S_{(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + HS^-_{(aq)}$	hydrogen sulfide ion	
	dihydrogen phosphate ion	7.9×10^{-2}	$H_2PO^-_{4(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + HPO^{2-}_{4(aq)}$	hydrogen phosphate ion	
5	hydrogen sulfite ion	4.4×10^{-2}	$HSO^-_{3(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + SO^{2-}_{3(aq)}$	sulfite ion	
	ammonium ion	7.5×10^{-3}	$NH^+_{4(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + NH_{3(aq)}$	ammonia	
	hydrogen carbonate ion	2.4×10^{-3}	$HCO^-_{3(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + CO^{2-}_{3(aq)}$	carbonate ion	Strong Bases
	hydrogen phosphate ion	4.7×10^{-4}	$HPO^{2-}_{4(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + PO^{3-}_{4(aq)}$	phosphate ion	
	hydrogen sulfide ion	3.3×10^{-4}	$HS^-_{(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + S^{2-}_{(aq)}$	sulfide ion	
	water (55.5 mol/L)	1.8×10^{-3}	$H_2O_{(\ell)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + OH^-_{(aq)}$	hydroxide ion	
	hydroxide ion	0	$OH^-_{(aq)} + H_2O_{(\ell)} \leftarrow H_3O^+_{(aq)} + O^{2-}_{(aq)}$	oxide ion	4

Notes:

1. All strong acids are completely reacted and therefore written as $H_3O^+_{(aq)}$ plus the anion of the acid.
2. All negative ions above water on the right side of the equation have essentially no ability to attract protons.
3. The hydronium ion is only listed so that H_2O may appear as a base on the right side of the equation.
4. $O^{2-}_{(aq)}$ does not exist and is written as $OH^-_{(aq)}$.
5. Quantitative acid-base reactions are those involving the reaction of $H_3O^+_{(aq)}$ with any base below the nitrite ion, and the reaction of $OH^-_{(aq)}$ with any acid above the hydrogen sulfite ion.
6. A single arrow is used for equilibriums which are greater than 99% in one direction. In this acid-base table the equilibrium arrows are for the reaction of the 0.10 mol/L aqueous acid with water.
7. Indicators are not used as 0.10 mol/L solutions. The indicators have been empirically placed on the table so approximate reaction predictions can be made.

10. Formulas

$$\underset{e^-}{n} = \frac{q}{Q} = \frac{It}{9.65 \times 10^4}$$

$$\underset{(kW \cdot h)}{E} = \frac{IVt}{1000}$$

$$\underset{(J)}{E} = IVt$$

11. SI Units & Symbols

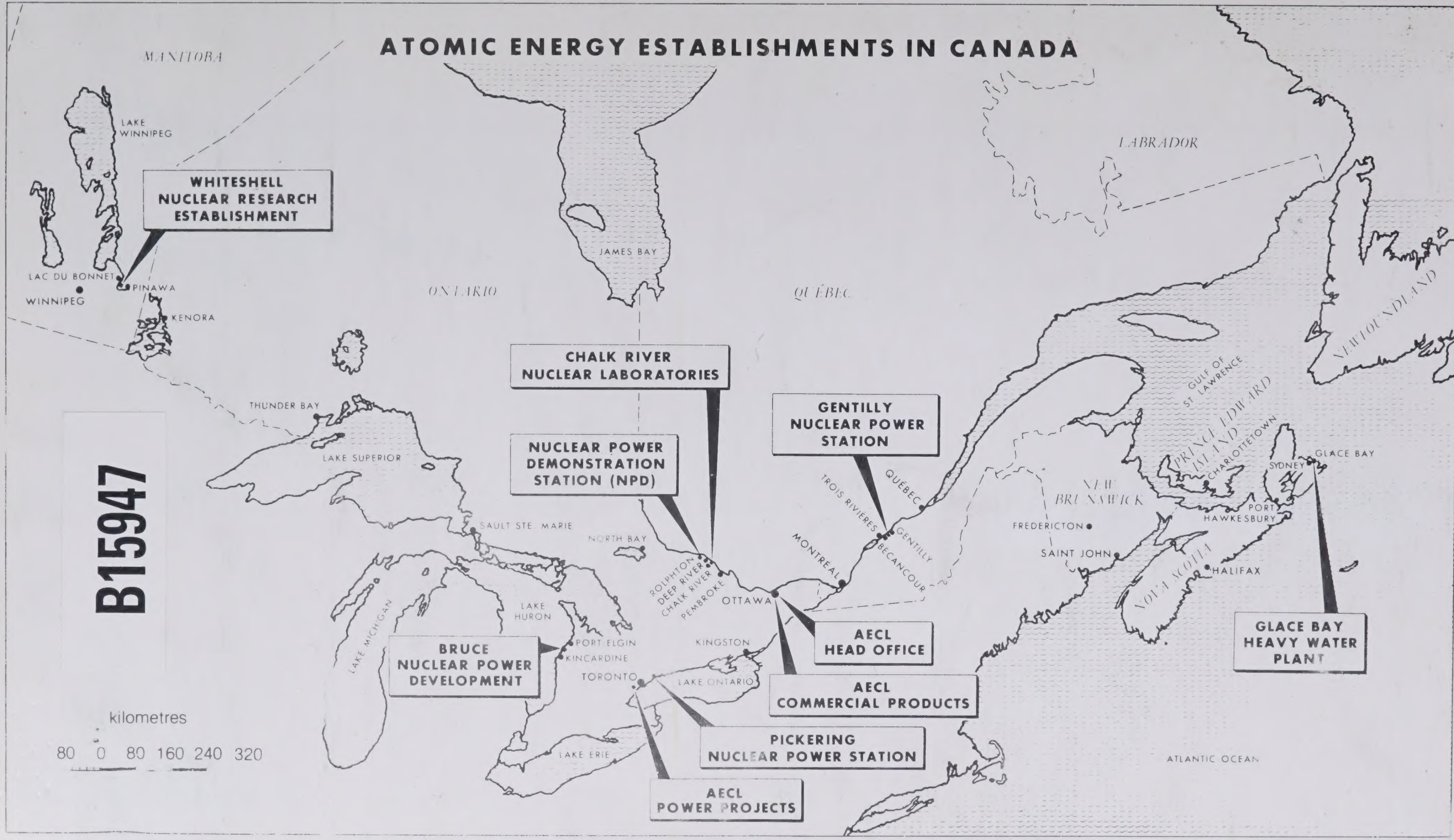
metre	m
gram	g
tonne	t
mole	mol
litre	L
second	s
ampere	A
volt	V
coulomb	C
joule	J
kilowatt hour	kW·h
pascal	Pa

12. SI Prefixes

Prefix	Symbol	Factor
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
* giga	G	10^9
* mega	M	10^6
** kilo	k	10^3
hecto	h	10^2
deca	da	10^1
deci	d	10^{-1}
** centi	c	10^{-2}
** milli	m	10^{-3}
* micro	µ	10^{-6}
* nano	n	10^{-9}
* pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

** most common
* next most common

ATOMIC ENERGY ESTABLISHMENTS IN CANADA



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